SCIENCE LIBRARY

THIS NUMBER COMPLETES VOLUME 38

Volume 38 December, 1934 Number 6

SOIL SCIENCE

Editor-in-Chief
JACOB G. LIPMAN

Associate Editor
HERMINIE BROEDEL KITCHEN

Contents

The Soil-Moisture System. G. B. Bodman and N. E. Edlefsen..... 425

The Cunninghamella Plaque Method of Measuring Available Phosphorus in Soil. A. Mehlich, E. B. Fred and E. Truog..... 445

Effect of the Degree of Base Saturation of a Soil on its Capacity to Fix Phosphorus in Difficultly Available Form. A. Floyd Heck..... 463

The Solubility of Phosphorus in Soils from Some Illinois Experiment Fields. H. J. Snider..... 471

A Method for Determining the Degree of Decomposition That Unknown Decayed Vegetable Organic Materials Have Already Undergone in Nature. George John Bouyoucos..... 477

Morphology and Genesis of the Solonetz Soils of Western North Dakota. Charles E. Kellogg..... 483

Index..... 503

NRA MEMBER U.S. WE DO OUR PART

Published Monthly by THE WILLIAMS & WILKINS COMPANY
MT. ROYAL AND GUILFORD AVENUES, BALTIMORE, MARYLAND. U. S. A.

Made in United States of America

SOIL SCIENCE

FOUNDED BY
RUTGERS COLLEGE
NEW BRUNSWICK, N. J.

ADVISORY STAFF

A. W. Blair, J. S. Joffe, L. L. Lee, H. C. McLean, G. T. Nightingale, A. L. Prince, J. W. Shive, H. B. Sprague, R. L. Starkey, and S. A. Waksman, New Jersey Agricultural Experiment Station, New Brunswick, N. J.

CONSULTING EDITORS

F. J. ALWAY
University of Minnesota, St. Paul, Minn.

K. ASO
Imperial University, Tokyo, Japan

C. BARTHEL
Lantbrukshögskolan, Uppsala, Sweden

P. E. BROWN
Iowa State College of Agriculture, Ames, Iowa

B. C. BURT
Imperial Council of Agricultural Research, New Delhi, India

H. J. CONN
New York State Experiment Station, Geneva, N. Y.

ALBERT DEMOLON
Ministry of Agriculture, Paris, France

E. B. FRED
University of Wisconsin, Madison, Wis.

V. V. GEMMERLING
Agronomitsheskii Institute, Moskovskii Universitat, Moscow, U. S. S. R.

J. E. GREAVES
Utah Agricultural College, Logan, Utah

ACH. GREGOIRE
Agricultural Experiment Station, Gembloux, Belgium

B. L. HARTWELL
26 Rowe St., Auburndale, Mass.

D. J. HISSINK
Soil Science Institute, Groningen, Holland

O. LEMMERMANN
Institut für Agrikulturchemie u. Bakteriologie der Landwirtschaftlichen Hochschule, Berlin-Dahlem, Germany

C. B. LIPMAN
University of California, Berkeley, Calif.

BURTON E. LIVINGSTON
Johns Hopkins University, Baltimore, Md.

HENRIK LUNDEGÅRDH
Centralanstalten för jordbruksförsök, Stockholm, Sweden

T. L. LYON
Cornell University, Ithaca, N. Y.

M. M. MCCOOL
Boyce-Thompson Institute, Yonkers. N. Y.

W. H. MACINTIRE
University of Tennessee, Knoxville, Tenn.

S. MATTSON
Lantbrukshögskolan, Uppsala, Sweden

E. A. MITSCHERLICH
University of Königsberg, Prussia

C. A. MOOERS
University of Tennessee, Knoxville, Tenn.

D. H. PRIANISHNIKOV
Petrovsko-Razumovskaia Akademia, Moscow, U. S. S. R.

THEO. REMY
Institut für Boden- und Pflanzenbaulehre, Bonn a. Rh., Prussia

G. ROSSI
Royal Agricultural High School in Portici, Naples, Italy

E. J. RUSSELL
Rothamsted Experimental Station, Harpenden, England

O. SCHREINER
U. S. Department of Agriculture, Washington, D. C.

ALEXIUS A. J. DE'SIGMOND
Royal Hungarian Joseph University of Technical Sciences, Budapest, Hungary

J. STOKLASA
Technical High School, Prague, Czechoslovakia

CHAS. E. THORNE
Ohio Experiment Station, Wooster, Ohio

N. M. TULAIKOV
Agricultural Experiment Station, Saratov, U. S. S. R.

G. WIEGNER
Landwirtschaftliche Hochschule, Zürich, Switzerland

S. WINOGRADSKY
Pasteur Institute, Paris, France

Entered as second-class matter, May 12, 1919, at the post office at Baltimore, Maryland, under the act of March 3, 1879.

Copyright, 1934, The Williams & Wilkins Company

THE SOIL-MOISTURE SYSTEM

G. B. BODMAN AND N. E. EDLEFSEN

University of California

Received for publication February 8, 1934

The soil may be regarded, with respect to soil moisture, as a porous medium consisting of inorganic and organic solid, liquid, and gaseous phases. The volume composition of the soil varies to a greater or lesser extent from time to time. Although this is true in some measure of all phases of the soil mass in the surface layers of cultivated soils, it is particularly true of the relative quantities of the liquid and gaseous phases at all depths from the surface above a permanent water table. The volumes of liquid and gases present in a given soil are complementary to each other and affected by such factors as precipitation, humidity, plant life, and many others characteristic of the soil itself.

THE SOLID FRAMEWORK

The nature of the solid phase can be outlined only briefly. It consists of relatively insoluble and also soluble constituents. The former include various-sized fragments of rock and minerals, plant and animal residues, microorganisms, and secondary products derived from them. The small quantities of soluble and ionizable solids have been produced by chemical and microbiological decomposition of the solid phase. Any colloidal particles which may be present are subject, because of their great specific surface, to certain changes of individual form, relative arrangement, and mobility, induced by variations in moisture content of the soil mass, or by the abundance and nature of the ions upon their surfaces. Such changes are not impressed to an appreciable extent upon the coarser particles of the soil. The insoluble particles of the soil phase in any given part of the soil section possess a certain size distribution, which as far as the inorganic part is concerned, may be measured with moderate success. They provide the soil mass with an abundance of interstitial pores, many of which may be ultra-microscopic in size.

CLAY AND THE MICROSTRUCTURE

It appears probable that, at very low moisture contents, the fine clay of the soil may have entrapped within its crystal lattices some water molecules which are so hindered from ready escape that they exert immeasurably slight vapor pressures at ordinary temperatures. This may also be true of the organic components and to a less extent of the coarser and less completely weathered

inorganic particles. Interplanar spacings have been reported (26, 31) for certain soil colloids, halloysite, and a bentonitic colloid, some of which are in excess of the molecular diameter of water (30). Simon and Schmidt (45) plotted temperature-composition curves for various synthetic ferric-oxides and obtained continuous curves for the region from 300° down to 20°C., which indicated the existence of adsorbed water rather than of any definite hydrates. Van Bemmelen's well-known researches (51) showed that exposure in the atmosphere above concentrated sulfuric acid was insufficient to remove the last traces of water from freshly prepared silica gel. Both colloidal ferric oxide and colloidal silica probably exist as such in many soils, as well as the more complex and definitely crystalline but colloidal aluminosilicates. Ross and Shannon (41) found that a sample of montmorillonite, which had been dried to constant weight at 100°C. lost an additional 9.6 per cent of water upon being further heated to red heat. Puri, Crowther, and Keen (38) obtained a linear increase in loss of weight with increasing temperature on heating a clay subsoil to a series of temperatures between 100° and 200°C., although Coutts' data (15), extending over a wider temperature range, indicate a lack of linearity. Organic matter may be expected to interfere with any interpretation of these curves as to the presence of water of crystallization. It was pointed out by Langmuir (33) that the apparent thickness of adsorbed films on glass surfaces is due to the permeability of the glass itself, the greater portion of the vapor retained by the glass being present within it. Failure to reckon with this possibility may affect to a serious extent calculations aimed at an estimate of the thickness of an adsorbed film on soil particles.

Altogether, there is considerable evidence in support of the idea that even the most minute recesses are accessible to molecules of water vapor.

ADSORPTION AND ESCAPE OF WATER MOLECULES

The relationship existing between the solid and liquid phases may be traced conveniently by a consideration of the conditions occurring because of the action of water vapor as the soil passes from a relatively dry to a relatively wet state. The first few molecules of water which bombard the solid phase will be retained with extreme tenacity. Some, as indicated above, may find their way actually within the lattice itself; the bulk, however, will be adsorbed as a thin layer upon the walls of minute capillary pores. Summaries of the results of adsorption measurements indicate, according to Adam (1), that the ease of adsorption is proportional to the ease of liquefaction of the gas, a fact which has been regarded as pointing, although inconclusively, to condensation of the vapor in the smallest pores by actual liquefaction. This condensation results in a progressive filling of the micropores, if not an actual thickening of the adsorbed surfaces, until finally the very smallest spaces are full. Further additions of water result in a relatively slower change in the configuration of the water surface. In visualizing the wetting process, it makes little difference actually whether it is supposed that all surfaces are first covered

with a mono-molecular layer which is followed by condensation in the capillaries, or whether a layer many molecules in thickness is assumed to be deposited on the surfaces. The result will be the same, the films ultimately coalescing to provide water wedges with characteristic curvatures dependent upon the fineness and arrangement of the soil particles and the amount of moisture. Still further additions of water molecules will gradually fill all

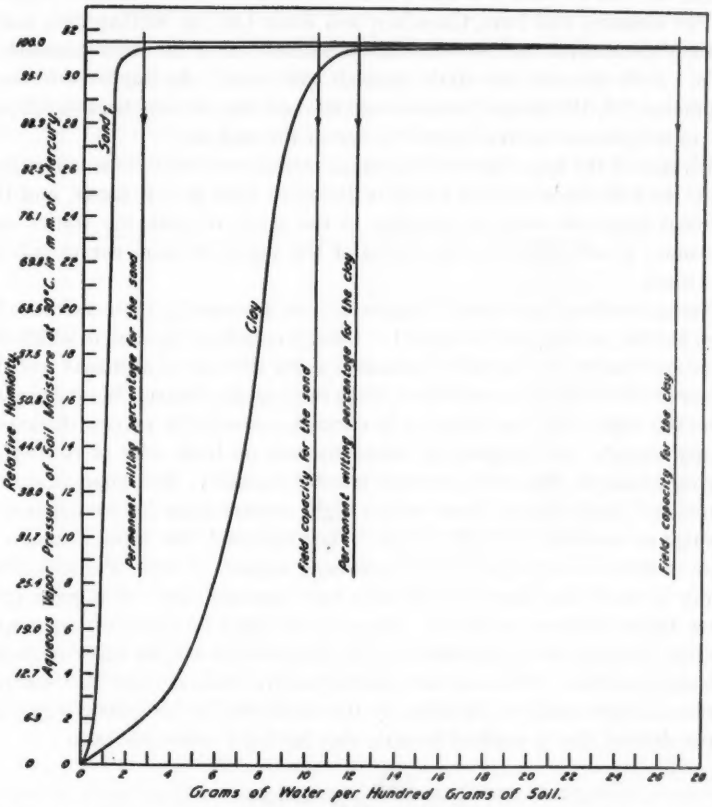

Relative Humidity
Aqueous Vapor Pressure of Soil Moisture at 30°C. in m.m. of Mercury
Sand
Clay
Permanent wilting percentage for the sand
Field capacity for the sand
Permanent wilting percentage for the clay
Field capacity for the clay
Grams of Water per Hundred Grams of Soil.

FIG. 1. TYPICAL VAPOR-PRESSURE CURVES FOR SAND AND CLAY, SHOWING WILTING PERCENTAGES AND FIELD CAPACITY

pores until the soil mass is saturated. Although the foregoing presentation assumes the absence of air, its presence will probably have no appreciable effect upon the sequence of events; it may, however, delay equilibrium.

The whole picture may now be viewed, very usefully, from the reverse aspect, with regard to the characteristic escaping tendencies displayed by the water molecules, which will vary in their freedom of movement at the liquid-

gas interface throughout the entire range of soil moisture content. The magnitude of these tendencies to vaporize may be measured conveniently by determining the vapor pressure associated with the soil at a given moistness.

The equilibrium vapor pressure represents, of course, the kinetic energy of the water molecules above the liquid-gas interface. As discussed later, this is dependent upon the relative magnitudes of the forces acting upon the water, the bulk of which is retained in the network of solids. Thomas (48, 49), in this country, and Puri, Crowther, and Keen (38), at Rothamsted, made some of the earliest and most accurate measurements of the vapor pressure of soils. Both dynamic and static methods were used. An improved form of apparatus (18, 19) devised to hasten equilibrium, has recently been developed for vapor pressure measurements by one of the authors.

Because of the importance of the vapor-pressure-moisture-content relationship, the full significance of which is discussed later in this paper, and the rational approach which it provides to the study of both the statics and dynamics of soil moisture, the forms of the vapor pressure curves will be described.

Various workers have found the general form assumed by these curves to be very similar, as indicated in figure 1. Using a coördinate system in which the moisture content of the soil is measured along the axis of abscissas and the vapor pressure, absolute or relative, along the axis of ordinates, and proceeding from the origin, they are found to be concave upwards for varying distances, nearly straight and steepest for some distance on both sides of the region corresponding to about 50 per cent relative humidity, then concave downwards and finally almost linear with a slight upward slope for the uppermost quarter or one-third of their extent. They approach the vapor pressure of pure water as an asymptote with increasing wetness of soil. For any given vapor pressure the finer-textured soils and separated clays of a given kind show higher moisture contents. There is, as might be expected, some connection between the composition of the fine material and its vapor-pressure-moisture relation. This was first pointed out by Anderson and Mattson (7). Determinations made at Berkeley by the static method for certain separated clays showed that a residual lateritic clay having a molecular ratio

$$\frac{SiO_2}{Fe_2O_3 + Al_2O_3} = 1.34$$

behaved very differently from several of the more highly siliceous varieties, the former exerting at much lower moisture contents vapor pressures equal to those shown by the latter at very much higher moisture contents. It is uncertain to what extent these differences, which are less prominent in the region of higher vapor pressures, are due to particle size and to what extent they are caused by characteristic differences in the nature of the surfaces of the two kinds of material.

Most of the measurements that have so far been made of soils or soil sep-

arates at humidities approaching saturation are of questionable exactitude because of the nature of the curve in that region, a very slight increase in vapor pressure corresponding to a great increase in moistness. From the point of view of the plant physiologist, this part of the curve is of greatest interest, since at moisture contents corresponding to these vapor pressures water is readily available to plants (52).

MECHANICAL FORCES ACTING ON SOIL MOISTURE

Some idea of the nature of the mechanical forces acting on the soil moisture may be obtained from the following considerations:

If we examine the horizontal forces acting on the rectangular parallelopiped (fig. 2) of unit cross section perpendicular to the plane of the paper, we note, under equilibrium conditions, that a pressure p acting on the interface EF is in the same direction as the cohesive forces of the remainder of the

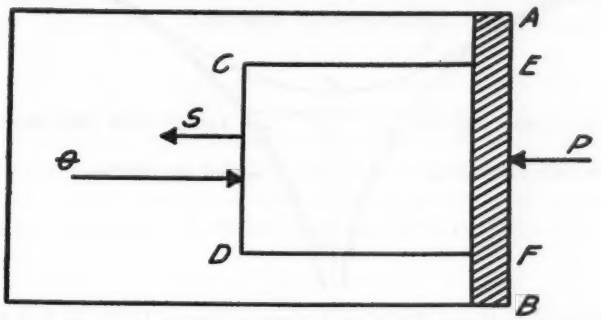


FIG. 2. DIAGRAM OF FORCES ACTING ON ELEMENTAL VOLUME OF WATER
S = cohesive force, θ = kinetic pressure, p = surface pressure acting on the interface EF.

liquid for the liquid in the volume $CDEF$. These two forces are balanced by the kinetic pressure θ of the liquid to the left of the volume $CDEF$ against the face CD so that we may write

$$p = \theta - S \qquad (A)$$

where p is a surface force and for most purposes θ may be regarded as such. On the other hand S is a body force, since it has a field. Other examples of body forces which may act on an element of soil moisture are the gravitational force and the adhesive force, since both possess fields.

Consider the water wedge in figure 3 and assume it small enough so that the effect of gravity on the shape of the air-water interface may be neglected. Let the horizontal plane pass through B'' at a distance below B' equal to the radius of the sphere of attraction of the cohesive forces. The hydrostatic pressures are in equilibrium around the line BB'' under this plane. This is also true of the kinetic pressures around $B''B'$. But above the plane the

molecular attractive forces depend upon the shape of the surface, which is governed by the relative magnitude of the cohesive and adhesive forces. Equation (A) holds above this plane as well as below it, but above the plane S is not constant with respect to distance from the line $B'B''$.

Another force acting on soil moisture is the attraction of dissolved substances such as salts, which produce an osmotic pressure. In some ways this may be regarded as an adhesive force.

As is pointed out later in this paper, a potential function, consisting of a gravitational potential, an osmotic potential, and a pressure potential, may be set up for soil moisture. The rate of change in any direction of the sum of these with respect to distance produces a conservative force field tending to move moisture in that direction. If any motion takes place, frictional forces are set up tending to resist the motion.

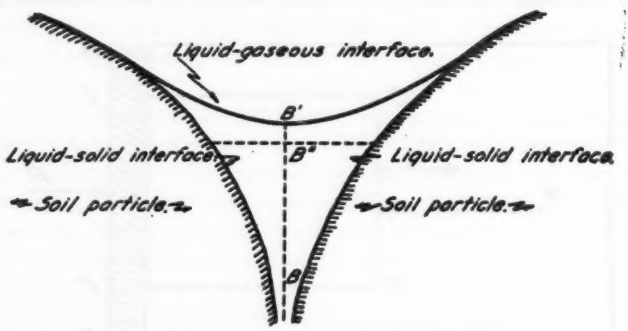


FIG. 3. DIAGRAM OF WATER WEDGE TO ILLUSTRATE FORCES ACTING ON SOIL MOISTURE

As has already been described, the sharp departure at a definite moisture content of a characteristic aqueous vapor pressure curve of soil moisture from the vapor pressure of free water suggests that the adhesive forces begin to predominate at this point. This point has special physiological significance, as has been shown by one of the authors, since it represents the moisture content at which plants wilt.

INTERRELATIONSHIPS OF BASIC FUNCTIONS

The effective curvature of the water-gas interfaces may be calculated from the vapor pressure exerted by the moisture in the soil. This may be obtained by the consideration of a clean glass capillary tube dipping down into a much larger vessel of pure water or of solution, vessel, tube, and liquid being confined in an evacuated chamber which contains in addition only the water vapor. The meniscus in the capillary is here considered for convenience to be a hemisphere of radius r, equal to the radius of the capillary tube. The following equation may be developed, however, without making this assumption. The

relationship between vapor pressure and curvature of liquid surface in such a system is given by the expression

$$\ln \frac{p_0}{p} = \frac{2\sigma}{r} \cdot \frac{M}{\rho RT} \qquad (B)$$

where

p_0 = vapor pressure above the flat surface of water or solution
p = vapor pressure above the curved meniscus in capillary
σ = surface tension of water or solution
M = molecular weight of liquid
r = radius of capillary tube
ρ = density of water or solution
R = gas constant expressed in suitable units
T = absolute temperature

It is accordingly apparent that for small values of r the vapor pressure p approaches zero, whereas with increase in r it approaches the limiting value p_0. This relationship is maintained at least to a first approximation for concentrations of the soil solution such as are usually encountered.

Differences in vapor pressure reported for the same soil at the same moisture content, the magnitudes of which depend upon whether the soil concerned is drying or wetting, have been referred to hysteresis effects. The possibility that true hysteresis may occur will be dealt with in the following discussion.

When the curved meniscus at the water-air interface is again considered, the pressure difference ϕ on opposite sides of the interface is given by the expression

$$\phi = \sigma\left[\frac{1}{r_1} + \frac{1}{r_2}\right] \qquad (C)$$

in which r_1 and r_2 are the two principal radiuses of curvature through the meniscus.

When

$$r_1 = r_2, \phi = \frac{2\sigma}{r} \qquad (D)$$

ϕ is negative when the liquid-vapor interface is concave to the vapor.

Referring now to the enclosed system described above, in which a capillary tube dips into a level water surface, we may express the vapor pressure at any height, h, above the plane surface of water in terms of the height by the exponential equation

$$p = p_0 \cdot e^{-\left[\frac{\rho g h}{p_0}\right]} \qquad (E)$$

in which

e = base of natural logarithms
ρ_0 = vapor density at level water surface
g = gravitational constant

and the remaining symbols have the same meanings as before.

The interrelationships of vapor pressure, curvature of meniscus, pressure difference on opposite sides of the curved meniscus, and height above a plane water surface at which a given vapor pressure and meniscus curvature are in equilibrium, are of greatest significance. They indicate the existence of a connection between a measurable property of the moisture content, namely, its vapor pressure, and an expression of that moistness in terms of energy relations. In other words, by measuring the vapor pressure exerted at a given point in a moist soil, an energy relationship may be calculated and expressed in terms of the work required per unit mass to move water through the soil from some position of reference, where the vapor pressure is also known, to the point in question. Thus, by taking the natural logarithms of both sides of equation (*E*) we have

$$h = -\frac{p_0}{\rho_0 g} \ln \frac{p}{p_0} \qquad (F)$$

in which h is the distance factor entering the work expression, and refers to the distance under equilibrium conditions from the water surface to the point in the soil mass at which the vapor pressure exerted by the moist soil is p.

A mathematical function called a "potential function" may be introduced conveniently during the consideration of a number of different aspects of the subject of soil moisture. Its use makes possible the development of a dynamical method which aids materially in the study of moisture flow in soils and which removes some of the difficulties in working out a rational soil moisture system. In soils it is known as the capillary potential function, or pressure potential function. It may be thought of as playing a rôle which, in relation to soil moisture flow, is similar to those played by voltage differences in electrical theory and pressure differences in the flow of water in pipes. It is merely a function created by the investigator and is introduced purely as a matter of convenience in analyzing the problem.

The pressure potential may be given the symbol ψ and is defined (21, 27, 39) by the equation

$$\psi = -\int_A^B f ds \qquad (G)$$

or

$$\psi = -\int_A^B \frac{dp'}{\rho} \qquad (H)$$

in which f represents the field force acting per unit mass of moisture, ds is an element of distance along the path, A is an arbitrarily chosen reference point of the zero potential usually taken as a free flat water surface and B is the point in question, p' is the pressure in the fluid, and ρ is the fluid density. This may be stated in words as the work per unit of mass done against the field forces in moving water from the reference point to the point in question.

Under equilibrium conditions and the influence of gravity equation (*G*) takes the form

$$\psi = -\rho gh \qquad (I)$$

Figure 4, which has already appeared elsewhere (19), provides a useful means of examining the interrelationships, at equilibrium, of the internal pressure conditions (*a*) in an osmotic solution, (*b*) in a moist soil, and (*c*) beneath the curved meniscus of a capillary tube. *A* is a chamber with semi-

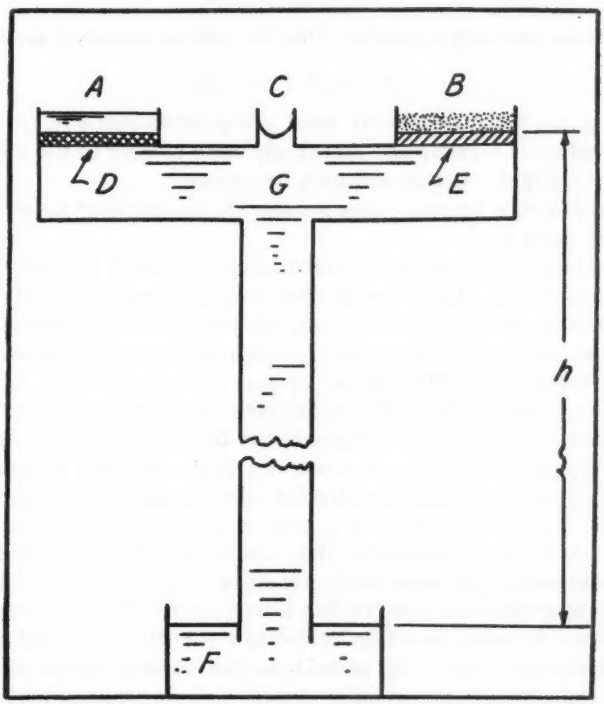


FIG. 4. A SYSTEM FOR DEMONSTRATING THE COLLIGATIVE PROPERTIES OF SOIL MOISTURE

permeable bottom, *D*, containing an osmotic solution; *B* is a chamber with a porous bottom, *E*, containing soil; *C* is the top of a capillary tube of height *h* and of appropriate diameter. *F* is a vessel of water. *G* is filled with water under tension. The system is enclosed in a chamber from which air is evacuated.

The pressure difference across the meniscus in *C* is given by equation (*D*). This difference in pressure, produced by surface tension, is just balanced by the weight of the column of liquid per unit area of height *h*, plus the difference

between the vapor pressure at the free water surface (p_0) and that above the meniscus (p) at C, so that[1]

$$\frac{2\sigma}{r} = \rho g h + (p - p_0) \qquad (J)$$

From which, together with equations (D) and (I), and in view of the fact that ϕ in this case is negative and represents the decrease in pressure due to curvature alone,

$$\psi = \phi + (p - p_0) \qquad (K)$$

From similar reasoning it is evident that the osmotic pressure is given by

$$\pi = \rho g h + (p - p_0) \qquad (L)$$

so that ϕ and π are numerically equal, and ψ differs from ϕ by $(p - p_0)$, an amount which is negative and exceedingly small relative to the other magnitudes concerned. It may ordinarily be neglected.

The relationship between vapor pressure (p) and capillary potential (ψ) is shown in figure 5.

In introducing the capillary potential function of soil, it is usually assumed to be single-valued. Under certain conditions, it is possible to conceive of an abrupt change at a given moisture content from a potential characterized by a negative curvature of the surface to a different potential characterized by another negative curvature but at the same moisture content. Under field conditions, however, where the soil has been subjected to forces which have produced a somewhat stable configuration of the soil, it is difficult to see how such a change could occur. It seems very likely that with inter-connected moisture films there could be only one effective curvature of the surface films and hence one potential at a given moisture content. Some investigators (25, 47) have interpreted their results as indicating a phenomenon which is known as hysteresis, which, if it exists at all, means that the potential function may depend on the previous history of the wetting process. Their experiments, however, have been carried on under laboratory conditions, and the results observed may very probably be due to changes in the structure of the soil rather than in the potential function when the structure remains fairly constant.

METHODS OF MEASURING CAPILLARY POTENTIAL FUNCTION

The capillary potential as used in the study of soil moisture was first introduced by Buckingham (13) in 1907. The methods used by him for measuring this function were very slow, and the slowness in arriving at equilibrium made the accuracy uncertain. In the same year, Livingston (36) developed some

[1] The more usual, but approximate, form of this equation is $\frac{2\sigma}{r} = \rho g h$, which is the form ordinarily used in deriving equation (E).

apparatus which he called an "auto-irrigator" which could be used for measuring capillary potential in soils. The relationship between these pieces of work appears to have been overlooked until a considerably later date, when it was pointed out by Gardner and others (21, 27) that the porous clay equipment developed by Livingston could be used for measuring the capillary potential function.

When the soil moisture in contact with a porous cup containing water under controlled pressure comes into equilibrium so far as movement of water is con-

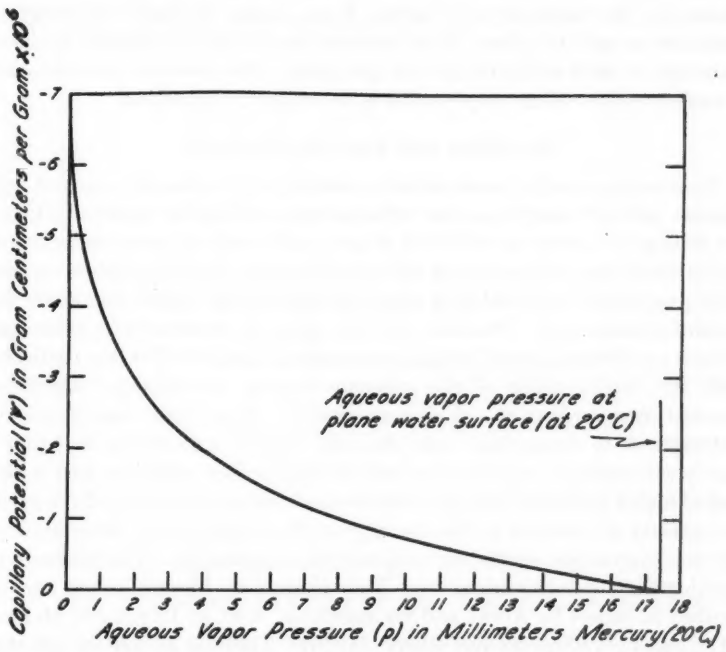

Capillary Potential (Y) in Gram Centimeters per Gram x 10⁶
-7
-6
-5
-4
-3
-2
-1
0
Aqueous vapor pressure at plane water surface (at 20°C)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Aqueous Vapor Pressure (p) in Millimeters Mercury (20°C)

FIG. 5. RELATIONSHIP BETWEEN VAPOR PRESSURE AND CAPILLARY POTENTIAL OF WATER AT 20°C.

cerned, we may state that the potential of the water in the soil is equal to the potential of water inside the cup and the magnitude of the potential has nothing to do with the porous wall separating the two. As has already been pointed out, the potential expressed in the metric system, that is gram-centimeters per gram, is numerically equal to the pressure, since the density of water is unity in this system.

It is observed with such a system of measuring the potential that ordinarily one cannot obtain a potential having a value of greater magnitude than that equivalent to one atmospheric pressure, or 1,034 gm.-cm. per gram, in fact,

unless special precautions are taken, it is difficult to obtain a potential as high as this. On the other hand, it is possible to plot vapor pressure curves over the entire range of soil moisture content from which the capillary potential can be calculated for any given moisture content.

In addition to these two ways of measuring the capillary potential, it might be mentioned that one of the authors has preliminary results on a new method for measuring this function in the field at moisture contents much lower than it is possible to work with by the porous cup method. The method makes use of the high dielectric constant of water in porous media (17). In fact, as shown by the vapor-pressure curves, if one wishes to study the range of moisture as used by plants, it is necessary to be able to measure capillary potential as great as 20,000 gm.-cm. per gram. The necessity of developing a method which will accomplish this is accordingly emphasized.

ARBITRARY SOIL-MOISTURE CONSTANTS

By exposing a soil to some suitably arranged and controlled standard conditions, such for example as exist within a region of definite vapor pressure, or by placing it in some external field of force which will act upon the moisture, it is evident that sooner or later the soil will reach a definite moisture content which represents a condition of actual or approximate equilibrium under the conditions concerned. Provided that the end point represents for these conditions a moisture content having some practical significance for that particular soil, the determination of this moisture content immediately becomes of interest as a method of soil characterization. There have been numerous attempts so to characterize soils physically and to indicate the fact that a sandy soil having a low moisture content may be in equilibrium with a clay soil of higher moisture content. Two methods which have received the greatest amount of attention in this country are those based on the determination of the hygroscopic coefficient and moisture equivalent. The methods of making these determinations have been referred to frequently and are described in papers by Alway and his associates (3, 4), by Briggs and McLane (11), and by Veihmeyer and others (55, 56). They are so well known that they need no further description. Their significance lies in their relationship to soil texture (10), to the amount of unavailable moisture which the soil retains (2, 12, 53), and to that moisture content at which the downward movement of irrigation or rain water is practically negligible (5, 9, 54).

The methods have objectionable features as well as advantages. In any analytical determinations it is highly desirable to have a state of true equilibrium reached. It is difficult in any case to avoid all possibility of the introduction of an arbitrary method of treatment at some point in soil investigations, in which the mere operation of removal from field to laboratory causes more or less serious disturbances in most soils; if equilibrium is not reached an additional arbitrary factor is brought into play. The difficulties of attaining equilibrium and of maintaining the defined conditions of the

determination provide the reasons for the greatest criticism which the hygroscopic coefficient has received (34, 35, 37). The objections were well realized by those who in this country put it to the most extensive and effective use (4). It is evident from figure 1 that wide ranges in moisture content may result at high relative humidities unless the humidity is very closely controlled. The definition of the conditions under which the moisture equivalent is determined emphasize its arbitrary character. Numerous experimental observations confirm this (10, 52). It is nevertheless apparent from an examination of the

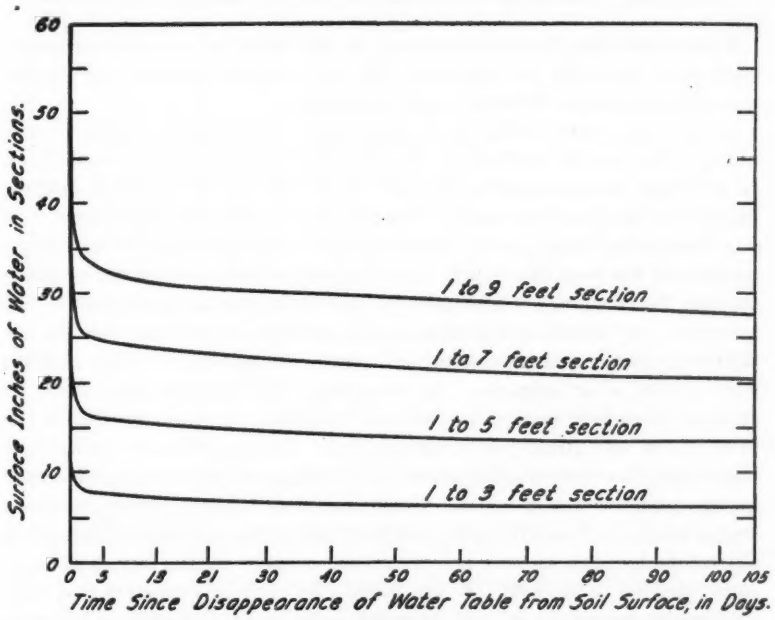

60
50
40
30
20
10
0
Surface Inches of Water in Sections.
1 to 9 feet section
1 to 7 feet section
1 to 5 feet section
1 to 3 feet section
0 5 13 21 30 40 50 60 70 80 90 100 105
Time Since Disappearance of Water Table from Soil Surface, in Days.

FIG. 6. RELATIONSHIP BETWEEN TIME SINCE DISAPPEARANCE OF WATER TABLE FROM SOIL SURFACE AND MOISTURE CONTENT OF SOIL, EXPRESSED AS SURFACE INCHES

literature that both determinations have shaped the development of a more critical point of view in experiments dealing with the utilization of water and in the interpretation of field moisture data.

Alway and others (6) suggested the use of the hygroscopic coefficient as a reference point in the expression of soil moisture content. Veihmeyer and Hendrickson found that the moisture equivalent is approximately equal numerically to the maximum amount of water which a soil will hold in the root zone and accordingly they have proposed and found useful the term "relative wetness" to describe the ratio of the percentage of moisture in a soil to the moisture equivalent of that soil. They demonstrated with a number of

soils in the field, as did Shaw (43) and Alway and McDole (5) in the laboratory, that movement of moisture is extremely slow after the upper portion of the soil mass has been brought to a moisture content approximately equal to its moisture equivalent. King (32), on the other hand, reported that water continued to drip from columns of sand for 2½ years from the time of their saturation. Data presented in figure 6 (9) indicate the rate of adjustment under field conditions of water in a silt loam soil originally saturated.

FIELD AND LABORATORY OBSERVATIONS ON SOIL MOISTURE MOVEMENT

A comprehensive statement or theory on the subject of soil moisture movement must obviously be consistent with the common practical and experimental observations in the field and laboratory.

It was early noted that in some cases water moved rather rapidly from a wet to a drier soil by capillarity. On the other hand, it has been shown more recently that the extent and rate of such movement may be extremely limited. The rate of rise from deep water tables (44) is of no practical importance. It was observed by many people that this action could be reduced by making an interface in the form of a mulch. Many reports of experiments are available showing the effectiveness of mulches in preventing upward movement of soil moisture. In examining this information, however, it is found that the experiments usually were conducted with some sort of pots to which mulches were applied after irrigation. In some cases, the mulches were made by stirring the surface layer of the wet soil; in others they were applied in the form of dry soil, straw, paper, and so forth. It was definitely shown that under such laboratory conditions the loss by surface evaporation was decreased by the application of a mulch. From these results many recommendations were made to farmers with respect to their cultivation practice. This type of laboratory information was not considered entirely satisfactory, and trials were extended to the field. It was thought by early investigators that their field results showed the value of the mulch in decreasing evaporation, but upon examination of their methods, it is usually found that the amount of decrease in evaporation thought to have been observed might have been explained by the method used in taking the moisture samples. For example, in a certain experiment one field was mulched and another was unmulched. Moisture samples were taken on both fields before mulching, and after a period of time the second samples were taken. In taking the samples on the mulched plot, the dry soil of the mulch was scraped away first, whereas in the unmulched plot, the samples were taken starting at the surface of the ground. This discrepancy in their conclusions was observed by some and corrected in later publications. Many substantiating data indicate that when mulches are applied by implements in the field as soon as the ground is capable of being worked, there is little or no difference between the moisture lost under mulched conditions and that lost when the soil is untouched by a cultivating device. It is found, for example, that approximately half of the soil moisture that will

be lost by evaporation from the surface is already lost before one can get on the field to cultivate it. Practically, there is no significant difference between mulched and unmulched fields in the case of mulches produced by cultivation. It has been demonstrated conclusively, however, that paper and straw mulches applied to the field are effective in preventing evaporation.

It has also been amply demonstrated (2, 14) that, practically, the rate of movement of soil moisture is too slow to supply growing plants with water

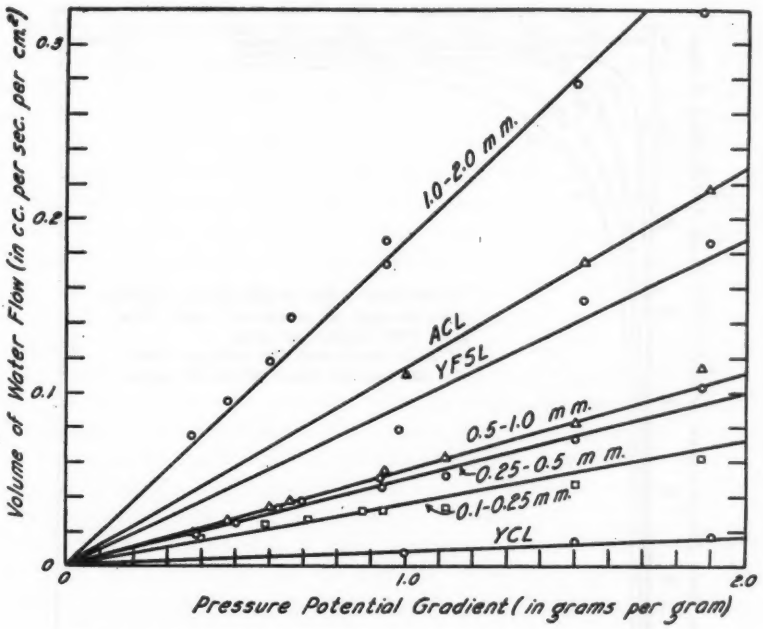


FIG. 7. TRANSMISSION OF WATER THROUGH SATURATED SANDS AND SOILS

The pressure potential gradient may be written in full as gram-centimeters per gram of water per centimeter of column of soil.

Multiply the horizontal scale by 5 for all soils.

Divide the vertical scale by 10 for soil YCL (Yolo clay loam) and YFSL (Yolo fine sandy loam). Divide vertical scale by 50 for soil ACL (Aiken clay loam).

through distances greater than a few inches. In other words, the roots of crops must grow to the water if they are to obtain it.

Considerable effort has been expended on the investigations of the adjustment of moisture distribution in a soil under the action of gravity, starting with a saturated soil. Most of this work has been done in the laboratory, and frequently it is difficult to interpret because of the artificial conditions set up, although many of the experiments do indicate the slowness with which equilibrium is reached. The experience of King, who found that his soil columns continued to drip for at least 2½ years, has already been mentioned.

The subject of the motion of water through soils under saturated conditions has received attention (8, 23, 24, 46, 57, 58), and it has been demonstrated with fair satisfaction that, for most cases at least, the velocity of the water is proportional to the force producing the motion. Unpublished results obtained by one of the authors illustrate the relationship between certain pressure gradient limits as shown in figure 7. It is to be observed that the slope represents the volume of flow per unit potential gradient per unit area.

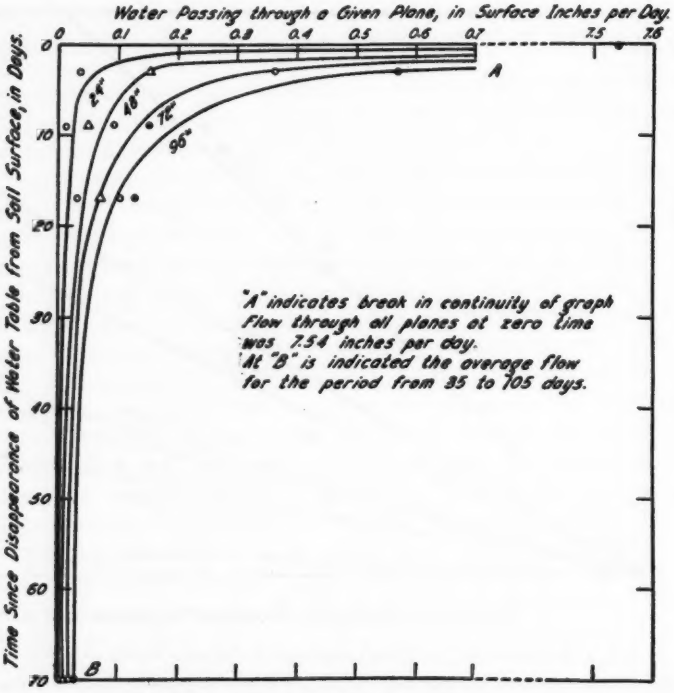


FIG. 8. QUANTITY OF WATER TRANSMITTED THROUGH SOIL PLANES IN SURFACE INCHES PER DAY AS RELATED TO DEPTH AND TIME

This is constant for a given material over the range observed and may be termed the "transmission function."

Field observations on the downward movement of water in soils are of great importance in irrigated regions, and many such experiments have been conducted (9, 28, 42). They involve a study of the motion under saturated conditions as well as the adjustment of the moisture distribution after irrigation water has disappeared from the surface. Results obtained in the field by the authors on the downward motion of water in a silt loam soil, already referred to, are shown in figure 8. The rate of penetration under saturated conditions

was observed by measuring the rate of sinking of the water surface above the soil. The downward motion after the water had disappeared from the surface was obtained by detailed soil moisture sampling at later dates. The plot was covered to prevent losses by evaporation. It is noteworthy that as late as 105 days after irrigation approximately 0.03 inch of water per day passed downward across a plane situated 9 feet below the soil surface.

THE THEORY OF SOIL MOISTURE MOVEMENT IN THE LIQUID PHASE

Progress has been made by several investigators (13, 22, 27, 39, 40, 46) toward working out a satisfactory theory of soil moisture movement. It is recognized that if a quantitative treatment is to be given, the forces and energy relations involved must be taken into account. For this reason, it is found desirable to introduce a capillary potential function, as has been pointed out. This quantity is related to the movement of soil moisture, since its rate of change with respect to distance gives a force acting on the moisture. This force and the force of gravity are the principal forces tending to produce motion of soil moisture under field conditions and account for the motion observed. When one is dealing with the motion of water from the soil into plants and from there into the air, it is convenient to introduce an osmotic potential function. The osmotic potential may also be useful in analyzing soil-moisture conditions when the salt concentration of the soil solution varies with distance. Where bodies move under the action of conservative forces, the resultant of the effective forces is a measure of the acceleration. This is not true when friction is a factor, as in the case of the movement of water in soils, and a velocity is soon reached at which the frictional force becomes equal and opposite to the resultant of the effective forces.

In such slow motion as that of water in soils, there is considerable evidence to justify the assumption that the frictional forces are proportional to the velocity. This may be expressed mathematically by the simple equation

$$V = K F = K \nabla (\psi + \omega + \lambda) \qquad (M)$$

where V represents the mean velocity per unit cross section; K represents the proportionality factor, the magnitude of which depends upon the frictional forces set up by the soil; F represents the driving force per unit mass composed of gradients of the capillary potential, ψ, due to hydrostatic pressure, the gravitational potential, ω, due to the position in the gravitational field, and the osmotic potential, λ, due to an osmotic pressure (34). The factor K may be regarded as a transmission function. Equation (M) simply states that the force acting on soil moisture and, consequently, the velocity are proportional to the greatest space rate of change of the sum of the three potentials and have a direction the same as the direction of the greatest change of this sum. Slichter obtained a solution for this differential equation for the case of flow through saturated soils. Gardner and Widtsoe have made a careful study of

it as applied to unsaturated soils and have shown that the equation takes specific forms when certain boundary conditions exist.

In their treatment, they assumed K to be proportional to moisture content and ψ to be a linear function of the reciprocal of the moisture density. They treated three special cases and obtained a solution for the case of the downward movement of a column of water in a soil with no surface energy developed at either top or bottom. This case is nearly realized during the time a field is covered with irrigation water to a very shallow depth.

They also analyzed the case where the water was removed from the surface and an equilibrium distribution of moisture had been obtained such that the gradient of the capillary potential produced a force equal and opposite to g, which is the gradient of the gravitational potential, ω. The osmotic potential was presumably assumed to be constant. They also obtained a solution for the equation when only horizontal flow was experienced, and presented experimental results obtained in the laboratory which indicated that their solutions fitted the facts reasonably well.

Richards recently has gone further and has investigated for several types of soils the manner in which K depends upon ψ.

MOVEMENT OF WATER IN THE VAPOR PHASE

Water vapor may move through the soil by diffusion at constant temperatures and static air conditions. This motion is extremely slow, as pointed out by Ewing and Linford (20, 35), who have made contributions which are valuable in forming a satisfactory physical basis for describing the motion of vapor through soils, and it is therefore of little practical importance. This state of extremely slow motion probably has been mistaken for a state of equilibrium in some cases. This may be far from the truth and may lead to errors of considerable importance. The diffusion is more rapid if there is a temperature gradient. By far the larger amount of vapor movement in soils is through the convection currents of the soil air which carry water vapor in varying amounts. The "breathing" of soil due to changes in barometric pressure may cause movement either into or out of the soil, but the quantity of moisture moved by this means is probably small.

Much information is available on evaporation from soils under laboratory and field conditions, but the movement of vapor through them has received but little attention.

REFERENCES

(1) ADAM, NEIL KENSINGTON 1930 The Physics and Chemistry of Surfaces. Oxford.
(2) ALWAY, F. J. 1913 Studies on the relation of the non-available water of the soil to the hygroscopic coefficient. Univ. Nebr. Res. Bul. 3.
(3) ALWAY, F. J. 1917 Some notes on the direct determination of the hygroscopic coefficient. *Jour. Agr. Res.* 11: 147–166.
(4) ALWAY, F. J., AND CLARK, V. L. 1916 Use of two indirect methods for the determination of the hygroscopic coefficients of soils. *Jour. Agr. Res.* 7: 345-359.
(5) ALWAY, F. J., AND MCDOLE, G. R. 1917 Relation of the water retaining capacity of a soil to its hygroscopic coefficient. *Jour. Agr. Res.* 9: 27–71.

(6) ALWAY, F. J., MCDOLE, G. R., AND TRUMBULL, R. S. 1918 Interpretation of field observations on the moistness of the subsoil. *Jour. Amer. Soc. Agron.* 10: 265–278.

(7) ANDERSON, M. S., AND MATTSON, SANTE 1926 Properties of the colloidal soil material. U. S. Dept. Agr. Dept. Bul. 1452.

(8) BLANCK, E. 1930 Handbuch der Bodenlehre VI. Die Physikalische Beschaffenheit des Bodens. Berlin.

(9) BODMAN, G. B., AND EDLEFSEN, N. E. 1933 *Science* (n. s.) 78 (No. 2025): 355. (See Abstracts of papers presented at the meeting of the Western Society of Soil Science at Salt Lake City, Utah, June, 1933, for abstract.)

(10) BODMAN, G. B., AND MAHMUD, A. J. 1932 The use of the moisture equivalent in the textural classification of soils. *Soil Sci.* 33: 363–374.

(11) BRIGGS, L. J., AND MCLANE, J. W. 1907 The moisture equivalent of soils. U. S. Dept. Agr. Bur. Soils Bul. 45.

(12) BRIGGS, L. J., AND SHANTZ, H. L. 1912 The wilting coefficient for different plants and its indirect determination. U. S. Dept. Agr. Bur. Plant Indus. Bul. 230.

(13) BUCKINGHAM, E. 1907 Studies on the movement of soil moisture. U. S. Dept. Agr. Bur. Soils Bul. 38.

(14) CONRAD, J. P., AND VEIHMEYER, F. J. 1929 Root development and soil moisture. *Hilgardia* 4: 113–134.

(15) COUTTS, J. R. H. 1932 Single value soil constants: A study of the significance of certain soil constants VI. *Jour. Agr. Sci.* 22: 200–202.

(16) EDLEFSEN, N. E. 1932 Forces acting on soil moisture in relation to other fundamental functions. *Trans. Amer. Geophysical Union 13th Ann. Meeting*, Washington, D. C., April, 1932: 328–330.

(17) EDLEFSEN, N. E. 1933 A review of results of dielectric methods of measuring moisture present in materials. *Agr. Engin.* 14: 243–244.

(18) EDLEFSEN, N. E. 1933 A glass wool cell for measuring aqueous vapor pressure. *Rev. Sci. Inst.* 4: 345–346.

(19) EDLEFSEN, N. E. 1934 A new method of measuring the aqueous vapor pressure of soils. *Soil Sci.* 38: 29–35.

(20) EWING, SCOTT 1922 The movement of saturated water vapor through quartz flour. *Soil Sci.* 13: 57–61.

(21) GARDNER, W., ISRAELSEN, O. W., EDLEFSEN, N. E., AND CLYDE, H. S. 1922 The capillary potential function and its relation to irrigation practice. *Phys. Rev.* 20: 196.

(22) GARDNER, W., AND WIDTSOE, J. A. 1921 The movement of soil moisture. *Soil Sci.* 11: 215–232.

(23) GREEN, W. H., AND AMPT, G. A. 1911 Studies on soil physics (pt. 1) The flow of air and water through soils. *Jour. Agr. Sci.* 4: 1–24.

(24) GREEN, W. H., AND AMPT, G. A. 1912 Studies on soil physics (pt. 2) The permeability of an ideal soil to air and water. *Jour. Agr. Sci.* 5: 1–26.

(25) HAINES, W. B. 1930 Studies in physical properties of soils: V. The hysteresis effect in capillary properties and the modes of distribution associated therewith. *Jour. Agr. Sci.* 20: 97–116.

(26) HENDRICKS, S. B., AND FRY, W. H. 1930 The results of X-ray and microscopic examinations of soil colloids. *Soil Sci.* 29: 457–479.

(27) ISRAELSEN, O. W. 1927 The application of hydrodynamics to irrigation and drainage problems. *Hilgardia* 2: 479–528.

(28) ISRAELSEN, O. W., AND WEST, F. L. 1922 Water holding capacity of irrigated soils. Utah Agr. Exp. Sta. Bul. 183.

(29) JOSEPH, A. F., AND MARTIN, F. J. 1923 The moisture equivalent of heavy soils. *Jour. Agr. Sci.* 13: 49–59.

(30) KAYE, G. W. C., AND LABY, T. H. 1926 Tables of Physical and Chemical Constants, Ed. 5. Longmans, Green and Co., London.

(31) KELLEY, W. P., DORE, W. H., AND BROWN, S. M. 1931 The nature of the base exchange material of bentonite, soils and zeolites, as revealed by chemical investigation and X-ray analysis. *Soil Sci.* 31: 25–56.

(32) KING, F. H. 1907 Physics of Agriculture. Madison, Wisc.

(33) LANGMUIR, I. 1918 The adsorption of gases on plane surfaces of glass, mica and platinum. *Jour. Amer. Chem. Soc.* 40: 1361–1403.

(34) LINFORD, L. B. 1926 The relation of light to soil moisture phenomena. *Soil Sci.* 22: 233–252.

(35) LINFORD, LEON B. 1929 Soil moisture phenomena in a saturated atmosphere. *Soil Sci.* 29: 217–237.

(36) LIVINGSTON, B. E. 1908 A method for controlling plant moisture. *Plant World* 11: 39–40.

(37) PURI, A. N. 1925 A critical study of the hygroscopic coefficient of soil. *Jour. Agr. Sci.* 15: 272–283.

(38) PURI, A. N., CROWTHER, E. M., AND KEEN, B. A. 1925 The relation between the vapour pressure and water content of soils. *Jour. Agr. Sci.* 15: 68–88.

(39) RICHARDS, L. A. 1928 The usefulness of capillary potential to soil moisture and plant investigators. *Jour. Agr. Res.* 37: 719–742.

(40) RICHARDS, L. A. 1931 Capillary conduction of liquids through porous mediums. *Physics* 1: 318–333.

(41) ROSS, C. S., AND SHANNON, E. V. 1926 The minerals of bentonite and related clays and their physical properties. *Jour. Amer. Ceramic Soc.* 9: 77–96.

(42) SCOFIELD, CARL S., AND WRIGHT, COULSEN C. 1928 The water relations of Yakima Valley soil. *Jour. Agr. Res.* 37: 65–86.

(43) SHAW, C. F. 1927 The normal moisture capacity of soils. *Soil Sci.* 23: 303–317.

(44) SHAW, C. F., AND SMITH, A. 1927 Maximum height of capillary rise starting with soil at capillary saturation. *Hilgardia* 2: 399–409.

(45) SIMON, A., AND SCHMIDT, TH. 1925 Ueber Eisenhydrate und Eisenoxyde (in Zsigmondy-Festschrift). *Kolloid Ztschr.* (sup.) 36: 65–80.

(46) SLICHTER, C. S. 1898 Theoretical investigations of the motion of ground water. *U. S. Geol. Survey 19th Ann. Rept.* pt. 2: 301–384.

(47) SMITH, O. W., FOOTE, PAUL D., AND BUSANG, P. F. 1931 Capillary rise in sands of uniform spherical grains. *Phys. Rev.* 37: 1015–1016.

(48) THOMAS, MOYER D. 1921 Aqueous vapor pressure of soils. *Soil Sci.* 9: 409–434.

(49) THOMAS, MOYER D. 1924 Aqueous vapor pressure of soils: II. Studies in dry soils. *Soil Sci.* 17: 1–18.

(50) THOMAS, M. D., AND HARRIS, K. 1926 The moisture equivalent of soils. *Soil Sci.* 21: 411–424.

(51) VAN BEMMELEN, J. M. 1910 Die Absorption. Dresden.

(52) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1927 Soil moisture conditions in relation to plant growth. *Plant Physiol.* 2: 71–82.

(53) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1928 Soil moisture at permanent wilting of plants. *Plant Physiol.* 3: 1–2.

(54) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1931 The moisture equivalent as a measure of field capacity of soil. *Soil Sci.* 32: 181–193.

(55) VEIHMEYER, F. J., ISRAELSEN, O. W., AND CONRAD, J. P. 1924 The moisture equivalent as influenced by the amount of soil used in its determination. Calif. Agr. Exp. Sta. Tech. Paper 16.

(56) VEIHMEYER, F. J., OSKERKOWSKY, J., AND TESTER, K. B. 1927 Some factors affecting the moisture equivalent of soils. *Proc. First Internatl. Cong. Soil Sci.* 1: 1–23.

(57) WYCKOFF, R. D., BOTSET, H. G., AND MUSKAT, M. 1932 Flow of liquids through porous media under the action of gravity. *Physics* 3: 90–113.

THE CUNNINGHAMELLA PLAQUE METHOD OF MEASURING AVAILABLE PHOSPHORUS IN SOIL[1]

A. MEHLICH, E. B. FRED AND E. TRUOG[2]

University of Wisconsin

Received for publication December 26, 1933

Biological methods of measuring the available plant food of soils, especially phosphates, have been the object of numerous investigations, and the literature pertaining to this subject is so extensive and so well known that citations to it are largely omitted in this paper. The idea of using microörganisms to determine the availability of the plant nutrients of soils appears both sound and practical. Unfortunately, most of the methods proposed for this purpose either are complicated and time consuming or do not give reliable results. This investigation represents an attempt to devise a simple and improved biological test for determining the phosphate needs of soils.

EXPERIMENTAL

A test which involves the direct use of soil instead of liquid cultures is desirable from the standpoint of simplicity. The use of certain species of molds is desirable from the standpoint of rapidity of growth, resistance to variations in reaction, and ease of observation of results. Beginning, therefore, with the plaque procedure, numerous experiments were conducted in which various molds were seeded on soil plaques. Some 15 species of molds were grown on soil plaques; namely, (*a*) *Aspergillus niger;* (*b*) *A. oryzae;* (*c*) *A. terreus;* (*d*) *A. sydowi;* (*e*) *A. parasiticus;* (*f*) *A. carbonarius;* (*g*) *A. nidulans;* (*h*) *A. wentii;* (*i*) *Penicillium purpurogenum;* (*j*) *P. islandicum;* (*k*) *P. aurantiobrunneum;* (*l*) *Hormodendrum* sp.; (*m*) *Rhizopus nigricans;* (*n*) *Mucor genevensis;* and (*o*) *Cunninghamella* sp. Both lateral and vertical growth was observed with cultures of *Rh. nigricans* and *Cunninghamella* sp. As a result of these tests, *Cunninghamella* sp. was chosen because of its quick response to the supply of available phosphate. This organism belongs to the same

[1] This work was supported in part by a grant from the Wisconsin Alumni Research Foundation.

[2] The authors are indebted to Prof. E. A. Mitscherlich of the University of Königsberg, Germany, for supplying the samples of soil and his results given in table 8; to Prof. R. D. Hockensmith of the Colorado Experiment Station and to Prof. A. H. Post of the Montana Experiment Station for supplying the samples and field results given in table 7; to the Experiment Stations of Ohio, Michigan, New York, Massachusetts, Alabama, Virginia, and West Virginia for supplying many of the samples of soil and field results given in table 6; and to Dr. H. C. Greene of this laboratory and also to Dr. A. F. Blakeslee of Cold Spring Harbor, for the cultures of fungi.

general group of fungi as the common gray bread mold, *Rhizopus*. It grows very rapidly, producing a tufted and raised mat of grayish hyphae which soon cover the surface of the culture medium.

Cultures of four species of *Cunninghamella* were grown on 10 soils containing varying amounts of available phosphate. The results of these preliminary tests indicated that the growth of this mold is greatly influenced by the amount of available phosphorus. Although the individual species were not exactly alike, their plus and minus strains showed good agreement. From a number of tests in various soils it was concluded that *C. elegans* and *C. blakesleeana* are best suited for the test, followed by *C. echinulata*, and finally *C. berthollotiae*, which is least suited, since its hyphal growth is less rapid and less dense. In subsequent tests, the minus strains of *C. elegans* and *C. blakesleeana* were used. The stock cultures have been carried on the following medium: malt extract, 25 gm.; agar, 20 gm.; and water, 1,000 cc. For comparative purposes, reserve cultures were carried on sterilized soil. No difference has been noted in the cultures carried on malt agar and on soil.

It was found that *Cunninghamella* is able to use nitrogen in the form of ammonia as well as in the form of nitrate. Ammonium nitrate was found to be especially suited, since both the cation and anion are utilized as sources of nitrogen, and, therefore, this salt does not bring about any great change in reaction. In order to induce the maximum growth, organic nitrogen, in a form like peptone, should be furnished in small amounts, as well as adequate amounts of inorganic salts customarily used in synthetic culture media.

Details of the test

The amount of nutrient solution required in the preparation of the plaque depends upon the kind of soil; usually the best results are obtained if the soil is just saturated. A film of liquid should never appear on the smoothed surface, as this will introduce considerable error, especially in soils high in available phosphates. Instead of aerial hyphae, mycelial growth of a type which does not allow accurate measurement will appear. In order to induce a uniform growth, a very small drop of a rich suspension of spores should be added to the center of the plaque. This method of inoculating the soil plaque prevents undue spreading of the fungous spores. Other methods of seeding the spores were tried, *e.g.*, use of a viscous spore suspension in starch solution or vegetable oil, and also very thin pieces of filter paper about 3 mm. in diameter dipped in a rich spore suspension.

It is important to maintain standard conditions of temperature and humidity during incubation. The optimum temperature for *Cunninghamella* is about 28° to 29°C., although good growth is obtained at temperatures of 27° to 30°C. Temperature variations influence the growth of the mold, and, wherever accurate results are desired, incubation should be at 28° to 29°C. The time of incubation should be 48 to 50 hours, although the growth is frequently completed at 42 hours.

Preparation of soil samples. The samples should be air-dried or dried in an oven at a temperature not exceeding 50°C. The soil is then passed through a 20-mesh sieve and thoroughly mixed. The reaction is determined, and if the pH is lower than 7.5 the sample may be used directly for the test as described later in this paper. Soils with a pH greater than pH 7.5 should be

TABLE 1

Amounts of citric acid required to neutralize various amounts of $CaCO_3$ in soils

AMOUNTS OF $CaCO_3$ IN SOIL	CITRIC ACID NEEDED FOR NEUTRALIZATION OF 50 GM. OF SOIL		
	Weight of crystals	10 per cent citric acid solution	50 per cent citric acid solution
per cent	*gm.*	*cc.*	*cc.*
0.25	0.16	1.60	.....
0.50	0.32	3.20	.....
0.75	0.48	4.80	.....
1.00	0.64	6.40	.....
1.25	0.80	8.00	.....
1.50	0.96	9.60	.....
1.75	1.12	11.20	.....
2.00	1.28	12.80	.....
2.50	1.60	16.00	.....
3.00	1.92	19.20	.....
3.50	2.24	22.40	.....
4.00	2.56	25.60	5.12
4.50	2.88	28.80	5.76
5.00	3.20	32.00	6.40
6.00	3.84	38.40	7.60
7.00	4.48	44.80	9.00
8.00	5.12	51.20	10.20
9.00	5.76	57.60	11.60
10.00	6.40	64.00	12.80
11.00	7.04	.....	14.00
12.00	7.69	.....	15.40
13.00	8.32	.....	16.60
14.00	8.96	.....	18.00
15.00	9.60	.....	19.20
16.00	10.24	.....	20.60
17.00	10.88	.....	21.80
18.00	11.52	.....	23.00
19.00	12.16	.....	24.40
20.00	12.80	.....	25.60

adjusted to pH 6.8 to 7.5. A satisfactory procedure for doing this is to determine the approximate $CaCO_3$ content by means of a simple method previously described (4). The required amount of citric acid as given in table 1 is then added.

Preparation of nutrient solution. After a number of different nutrient

solutions had been tested, one prepared as next described was adopted. A stock solution of the following inorganic salts is first prepared:

KCl	20.0 gm.
$MgSO_4 \cdot 7H_2O$	10.0 gm.
$FeSO_4 \cdot 7H_2O$	0.2 gm.
$ZnSO_4 \cdot 7H_2O$	0.2 gm.
Distilled water	100.0 cc.

This stock solution of salts may be kept indefinitely. To avoid decomposition, the final diluted nutrient solution should be made up fresh at least every 2 days, as follows:

Glucose (or cerelose)	25.0 gm.
NH_4NO_3	2.5 gm.
Peptone	0.5 gm.
Stock solution of inorganic salts	5.0 cc.
Phosphorus-free water	1,000.00 cc.

Procedure. About 50 gm. of the soil is placed in one-half of a large Petri dish or other convenient glass container and 10 to 15 cc. nutrient solution added, or just enough for saturation but avoiding an excess as previously explained. After being thoroughly mixed, the soil is transferred to duplicate small Petri dishes (50 mm. dia. by 10 mm. high), and soil plaques are prepared, the surface being smoothed by means of a spatula. The duplicate samples are placed in a pan or dish, the bottom of which is covered with well-moistened blotting paper. By means of a wire loop (3 mm. in dia.) a very small drop of a rich spore suspension of *Cunninghamella* is placed in the center of the soil plaque. In order to make these drops uniformly small, the loaded wire loop is first touched to a clean glass surface to remove any excess of the suspension. The spore suspension is prepared by adding 2 cc. of the nutrient solution to a test tube culture of the fungus grown on malt extract agar. The age of this slant culture should be at least 1 week and not more than 4 weeks. The dish containing the soil plaques is covered with a glass plate, which is removed only for inoculation and observation. To provide for aeration, a strip of paper or wood should be placed between the glass cover and the dish.

The cultures are incubated at 28° to 29°C. for 48 to 50 hours, after which the growth is determined by measuring the diameter of the fungous colony. In rare instances the natural fungous flora of the soil will suppress the growth of *Cunninghamella*. This is avoided when a new sample of soil is taken and heated at 40°C. for several days.

Plate 1 shows the marked response of *Cunninghamella* to the addition of increasing amounts of phosphorus, and the meager growth of the fungus on soils containing small amounts of available phosphorus and abundant growth on soils with good supply of available phosphorus.

Interpretation of results. Tests made with soils of known crop response to phosphorus fertilization suggest the following approximate values of lateral

fungous growth in relation to the requirements of phosphate fertilizer: great need is indicated by a growth less than 10 mm. in diameter; moderate need by a growth between 11 to 15 mm. in diameter; slight need by a growth between 16 and 21 mm. in diameter; and no need by a growth above 22 mm. in diameter. These values will vary somewhat, depending on kind of crops involved and species of *Cunninghamella* used for the test.

Expression of results in p.p.m. of phosphorus

The desirability of expressing the results of the test in terms of pounds per acre or p.p.m. of available phosphorus in the soil is evident. An attempt was made to do this on the basis of the phosphorus absorbed from the soil by the fungus and found by analysis of the tissue. Unfortunately, great difficulty was experienced in separating the hyphae from the soil, and this attempt was thus abandoned.

In estimating the amount of growth, it has been found that for practical purposes it is not necessary to measure the vertical growth, but simply the diameter of the fungous colony. This lateral spreading indicates the relationship of growth to amount of available phosphorus present, and was, therefore, utilized in constructing the growth curves of Mitscherlich (5, 10) for 10 different types of soil.

To each of the 10 different types of soil increasing amounts of phosphorus were added, and then the growth of *Cunninghamella* under these treatments was measured and the effect factor calculated from the relationship:

$$c = \frac{\log (A - y_1) - \log (A - y_2)}{X_2 - X_1},$$

where $\log A$ is the maximum growth, y_1, y_2, etc., are the growths obtained when X_1, X_2, etc., amounts of phosphorus are added. The values of the effect factor (c), as shown for each soil in table 2, are expressed as phosphorus in milligrams per 100 gm. of soil. The value for c varies only from 0.150 to 0.172, and justifies its use, therefore, in calculating the amount of phosphorus in the soil from the relationship:

$$b = \frac{\log A - \log (A - y_0)}{c},$$

where y_0 is the growth obtained without the addition of phosphorus. When the maximum growth and the effect factor are known, the amount of available phosphorus in any other soil can be calculated.

By constructing an average curve from these data such as is given in figure 1, the effect-factor c can be eliminated and the amount of available phosphorus present in any soil may be obtained by simple interpolation on this curve.

It is recognized that the results obtained by the foregoing procedure are influenced to some extent by the phosphate-fixing power of the soils, causing

TABLE 2

The growth of Cunninghamella *on different soils with increasing amounts of phosphorus*

AMOUNT OF PHOSPHORUS ADDED TO SOILS	DIAMETER OF LATERAL GROWTH ON DIFFERENT SOIL TYPES									
	1	2	3	4	5	6	7	8	9	10
	Marshall silt loam	Miami silt loam	Carrington silt loam	Fox silt loam	Miami silt loam	Coloma sandy loam	Dodgeville silt loam	Plainfield sand	Knox silt loam	Waukesha sandy loam
p.p.m.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.
0	4	5	6	7	8	8	10	10	12	11
10	10	11	13	11	16	16	16	20	16	20
20	20	22	22	19	27	22	24	26	27	25
30	26	28	29	27	33	27	30	32	34	30
40	32	34	34	33	38	32	35	35	41	34
50	38	39	38	38	41	35	39	38	45	36
60	41	43	41	41	44	39	43	41	47	38
70	44	45	43	44	45	42	45	43	50	39
80	45	47	45	46	46	44	47	44	51	40
90	47	49	47	48	48	46	50	46	53	42
100	48	50	48	48	48	46	50	47	53	42
b*	2.4	2.9	3.6	4.2	5.0	5.2	6.1	6.6	7.0	8.5
c†	.158	.159	.155	.166	.172	.169	.151	.159	.155	.150

*b = p.p.m. of available phosphorus in soils as obtained from the relationship:

$$b = \frac{\log A - \log (A - y_0)}{c}$$

†c = the average effect-factor for each soil.

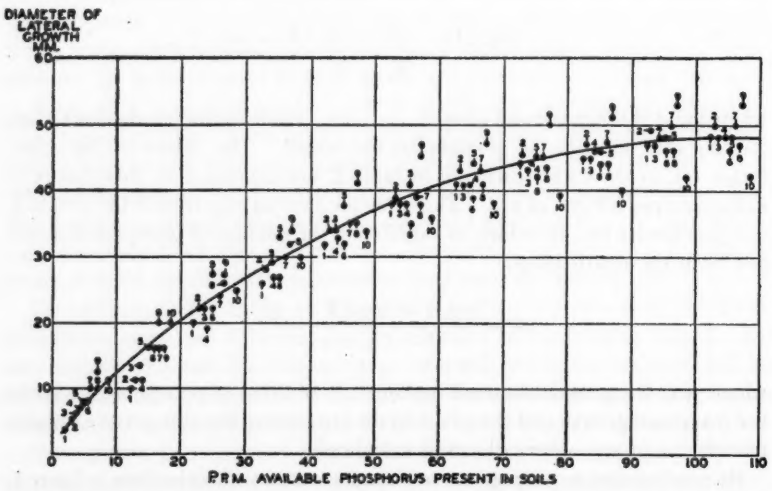


FIG. 1. RELATION OF LATERAL GROWTH OF CUNNINGHAMELLA ON 10 DIFFERENT SOILS BEFORE AND AFTER THE ADDITION OF 10 INCREMENTS OF AVAILABLE PHOSPHORUS

In the series 0 to 10 p.p.m. available phosphorus, the soils contained only their natural supply, which varied from 2.4 to 8.5 p.p.m., calculated according to the Mitscherlich formula. In succeeding series, each soil received increasing amounts (10, 20, 30, etc., p.p.m.), and is represented by dots similarly numbered throughout.

some of the applied phosphorus to become difficultly available. None of these soils, however, have high phosphate-fixing powers and hence this influence has probably not been serious.

Relation of soil reaction and salts to results

In the *Cunninghamella* method, as ordinarily carried out, only small amounts of a nearly neutral nutrient solution are added, and, therefore, the soil reaction undergoes very little change. Increasing amounts of lime may be added to a

TABLE 3

Influence of reaction on the growth of Cunninghamella *on unphosphated and phosphated soils*

REACTION OF SOIL AFTER ADDITION OF LIME	DIAMETER OF LATERAL GROWTH OF CUNNINGHAMELLA	
	No phosphorus added	80 p.p.m. of phosphorus added
pH	mm.	mm.
4.3	10	42
5.8	10	38
6.5	12	43
7.3	11	40
7.6	5	18
7.9	6	20

TABLE 4

The growth of C. elegans *and* C. echinulata *on soil to which different forms of phosphate were added at the rate of 200 pounds per acre*

CULTURE	DIAMETER OF GROWTH WITH DIFFERENT PHOSPHATES									
	$CaH_4(PO_4)_2 \cdot H_2O$	$CaHPO_4 \cdot 2H_2O$	$Ca_3(PO_4)_2$	$Mg_3(PO_4)_2 \cdot 4H_2O$	$MgNH_4PO_4 \cdot 6H_2O$	$AlPO_4$	$FePO_4 \cdot 4H_2O$	Rock phosphate	$Fe_3(PO_4)_2$	$(NH_4)_2HPO_4$
	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.
C. elegans	50	43	30	44	40	20	22	15	14	48
C. echinulata	48	42	32	48	41	23	26	18	16	50

soil until it reaches a pH 7.4 to 7.5 without much influence on the growth of *Cunninghamella*. Above a pH 7.5 the effect is quite different, the growth being greatly retarded because of a decreased solubility of the phosphate. Data regarding this matter are given in table 3. These observations agree with the findings of other investigators (1, 2, 3) regarding the decreased availability of phosphate when an excess of calcium carbonate is present. *Cunninghamella* will grow over a wide range of reactions, pH 3.2 to 8.6, and apparently is not easily influenced directly by acid or alkali but is very sensitive to a lowering in the solubility of the phosphates. That this fungus resembles closely the higher plants in respect to the use of phosphorus from various sources, is clearly evident from the data of table 4.

Tests (data not presented) showed that additions of increasing amounts of Mg, Na, Fe, and Zn sulfates, as well as potassium chloride, do not have any marked influence on the growth of *Cunninghamella*.

Comparison of results with other methods

For a comparison of results with other methods, 10 soils containing varying amounts of available phosphorus were selected. These soils were tested with the three biological methods: the *A. niger* method of Niklas (6, 7, 8); the Simakova-Bovschik method (9); the *Cunninghamella* method, and also the chemical method of Truog (11). The results are given in table 5 and show a

TABLE 5

A comparison of the Cunninghamella *method with various other methods of measuring the available phosphate of soils*

SOIL NUMBER	CUNNINGHAMELLA METHOD		SIMAKOVA-BOVSCHIK A. NIGER METHOD		NIKLAS A. NIGER METHOD		TRUOG CHEMICAL METHOD	FIELD TEST
	Diameter of lateral growth	Amount of available phosphorus by curve interpolation	Weight of mycelium from two cultures	Amount of available phosphorus by analysis of mycelium	Weight of mycelium from three cultures	Amount of available phosphorus by analysis of mycelium	Amount of available phosphorus	Increase per acre alfalfa hay due to phosphate fertilization
	mm.	*p.p.m.*	*mgm.*	*p.p.m.*	*mgm.*	*p.p.m.*	*p.p.m.*	*pounds*
10	4	3.0	70	9.5	380	41.6	9.5	900
29	6	4.5	86	8.8	564	80.8	16.5	600
34	8	6.5	76	12.0	512	68.3	9.0	500
46	10	9.5	100	14.0	583	84.0	18.0	450
52	12	10.5	113	16.3	525	58.2	12.5	250
64	16	15.0	155	20.6	654	83.2	14.0	100
80	21	21.5	140	17.5	634	100.0	20.0	...
86	25	28.0	208	41.2	795	212.2	30.0	0
96	34	45.0	216	41.0	780	137.5	27.0	0
99	50	100.0+	416	115.6	2,154	660.0	152.0	0

close agreement of the *A. niger* method with the chemical method, although the total amount of phosphorus removed by the *A. niger* Niklas method is greater than that by any of the other methods. This high amount of phosphorus in the mold pad is due, no doubt, to the presence of 1 per cent of citric acid in the medium. The *A. niger* Simakova-Bovschik method and the *Cunninghamella* method show a good agreement with field results.

In order to determine further the reliability of the *Cunninghamella* method, soils of known phosphate needs from widely separated parts of the United States were obtained and tested by the *Cunninghamella* method and also by the Truog chemical method. The results of these tests, and also the response of these soils in the field, are presented in table 6. All in all, the results of the biological test agree fairly well with the field results. In cases where field

TABLE 6

Phosphate needs of 100 soils as revealed by Cunninghamella, *chemical, and field tests*

SOIL NO.	SOIL TYPE	REACTION OF SOIL	CUNNINGHAMELLA METHOD		TRUOG CHEMICAL METHOD	FIELD TEST RESPONSE TO PHOSPHATE
			Diameter of lateral growth	Amount of available phosphorus by curve interpolation	Amount of available phosphorus	
		pH	*mm.*	*p.p.m.*	*p.p.m.*	
1	Bladen fi. sa. lo.	4.0	0	0.0	Trace	Good
2	Gloucester fi. sa. lo.	5.0	0	0.0	16	Good
3	Norfolk fi. sa. lo.	5.5	3	2.0	Trace	Good
4	Wooster si. lo.	7.4	3	2.0	Trace	Good
5	Miami si. lo.	5.4	3	2.0	Trace	Good
6	Frederick si. lo.	5.2	4	3.0	Trace	Good
7	Norfolk sa. lo.	4.8	4	3.0	Trace	Good
8	Decatur cl. lo.	5.7	7	5.5	Trace	Good
9	Miami si. lo.	5.6	4	3.0	Trace	Good
10	Knox si. lo.	5.9	4	3.0	9.5	Good
11	Wooster si. lo.	6.3	4	3.0	4	Good
12	Wooster si. lo.	6.4	4	3.0	4	Good
13	Norfolk sa. lo.	5.8	4	3.0	18	Good
14	Merrimac fi. sa. lo.	5.2	4	3.0	24	Good
15	Napanee si. lo.	5.1	5	3.5	4	Good
16	Wooster si. lo.	6.6	5	3.5	8	Good
17	Huntington si. lo.	4.6	5	3.5	14	Good
18	Ontonagon cl. lo.	5.6	5	3.5	14	Good
19	Wisner si. lo.	8.3	5	3.5	76	Good
20	Dutchess si. lo.	5.5	5	3.5	8	Good
21	DeKalb si. lo.	6.0	6	4.5	4	Good
22	Saugatuck v. fi. sa.	4.6	6	4.5	Trace	Fair
23	Mannor lo.	5.5	6	4.5	Trace	Good
24	Wooster si. lo.	6.6	6	4.5	7	Good
25	Elkton si. lo.	4.0	6	4.5	8	Good
26	Hagerstown si. lo.	5.7	6	4.5	8	Good
27	Miami si. lo.	5.4	6	4.5	8	Good
28	Knox si. lo.	5.9	6	4.5	12	Good
29	Dodgeville si. lo.	6.6	6	4.5	16.5	Good
30	Wooster si. lo.	7.1	7	5.5	9	Good
31	Saugatuck fi. sa.	5.2	7	5.5	4	Fair
32	Porters lo.	6.0	7	5.5	Trace	Good
33	Canfield si. lo.	4.8	7	5.5	11	Good
34	Dodgeville si. lo.	6.7	8	6.5	9	Good
35	Wooster si. lo.	7.0	8	6.5	10	Good
36	Fox sa. lo.	5.6	8	6.5	23	Good
37	Upshur cl. lo.	4.0	9	7.3	17	Good
38	Dodgeville si. lo.	6.0	9	7.3	11.5	Fair
39	Knox si. lo.	5.9	9	7.3	12	Good

TABLE 6—*Continued*

SOIL NO.	SOIL TYPE	REACTION OF SOIL	CUNNINGHAMELLA METHOD		TRUOG CHEMICAL METHOD	FIELD TEST RESPONSE TO PHOSPHATE
			Diameter of lateral growth	Amount of available phosphorus by curve interpolation	Amount of available phosphorus	
		pH	*mm.*	*p.p.m.*	*p.p.m.*	
40	Orangeburg sa. lo.	5.6	9	7.3	6	Fair
41	Fox sa. lo.	4.6	10	8.5	18	Good
42	Brookston si. lo.	6.9	10	8.5	24	Fair
43	Merrimac fi. sa. lo.	4.8	10	8.5	40	Fair
44	Volusia si. lo.	4.8	11	9.5	16	Good
45	Maimi si. lo.	6.4	11	9.5	12	Fair
46	Miami si. lo.	6.3	11	9.5	18	Fair
47	Suffield cl. lo.	7.0	11	9.5	120	Fair
48	Caribou lo.	5.0	12	10.5	25	Fair
49	Hillsdale sa. lo.	6.0	13	11.5	20	Fair
50	Miami si. lo.	6.8	12	10.5	16	Fair
51	Miami si. lo.	5.8	12	10.5	12	Fair
52	Waukesha sa. lo.	5.5	12	10.5	12.5	Fair
53	Hawaii soil	5.2	12	10.5	20	None
54	Caribou lo.	4.9	13	11.5	34	Little
55	Westmoreland si. lo.	4.3	14	12.5	16	Fair
56	Dodgeville si. lo.	5.7	14	12.5	12	Fair
57	Sparta sa.	6.1	14	12.5	16	Fair
58	Wooster si. lo.	5.5	14	12.5	23	Good
59	Napanee si. lo.	6.3	14	12.5	40	Little
60	Muskingum fi. sa. lo.	4.3	15	14.0	Trace	Fair
61	Miami lo.	5.4	15	14.0	17	Fair
62	Hartselle fi. sa. lo.	5.8	15	14.0	24	Fair
63	Sassafrass lo.	5.4	16	15.0	16	Fair
64	Carrington si. lo.	5.4	16	15.0	14	Little
65	Marshall si. lo.	5.3	16	15.0	14	Fair
66	Marshall si. lo.	5.2	16	15.0	12	Fair
67	Muck	5.5	16	15.0	12	Fair
68	Cheshire fi. sa. lo.	5.4	16	15.0	47	Little
69	Marshall si. lo.	5.6	17	16.0	14	Little
70	Vergennes cl.	5.8	17	16.0	90	Little
71	Agawam fi. sa. lo.	5.3	18	17.5	33	Little
72	Carrington si. lo.	5.8	18	17.5	18	Little
73	Hagerstown si. lo.	5.0	18	17.5	22	Little
74	Ontario lo.	5.3	18	17.5	26	Little
75	Brookston lo.	6.3	18	17.5	30	Little
76	Wheeling fi. sa. lo.	6.0	19	19.0	20	Fair
77	Miami si. lo.	6.5	19	19.0	28	Little
78	Miami si. lo.	7.1	19	19.0	37	None
79	Miami si. lo.	5.8	20	20.0	27	Little
80	Carrington si. lo.	5.8	21	21.5	20	Little

TABLE 6—*Concluded*

SOIL NO.	SOIL TYPE	REACTION OF SOIL	CUNNINGHAMELLA METHOD		TRUOG CHEMICAL METHOD	FIELD TEST RESPONSE TO PHOSPHATE
			Diameter of lateral growth	Amount of available phosphorus by curve interpolation	Amount of available phosphorus	
		pH	*mm.*	*p.p.m.*	*p.p.m.*	
81	Carrington si. lo.	6.1	22	23.0	38	None
82	Dodgeville si. lo.	5.0	23	25.0	19	Little
83	Dodgeville si. lo.	5.0	24	26.0	15.2	Little
84	Thomas lo.	8.3	24	26.0	39	None
85	Cheshire fi. sa. lo.	5.5	24	26.0	132	None
86	Knox si. lo.	6.5	25	28.0	30	None
87	Wauseon lo. sa.	7.5	25	28.0	65	None
88	Miami si. lo.	6.4	26	29.5	74	None
89	Cheshire fi. sa. lo.	5.8	26	29.5	40	None
90	Superior cl.	5.0	28	33.0	26	.....
91	Miami si. lo.	5.0	28	33.0	28	None
92	Greenville sa. lo.	5.6	28	33.0	62	None
93	Merrimac fi. sa. lo.	6.4	30	37.0	64	None
94	Norfolk lo.	5.9	31	39.0	32	None
95	Hillsdale sa. lo.	6.5	33	43.0	53	None
96	Coloma sa. lo.	6.0	34	45.0	27	None
97	Hawaii soil	6.4	34	45.0	124	None
98	Carrington si. lo.	7.0	48	91.0	170	None
99	Willamette si. lo.	5.8	50	100.0+	152	None
100	Hawaii soil	5.8	50	100.0+	210	None

tests indicated a lack of phosphate, a poor development of *Cunninghamella* usually took place, and conversely, in cases where the field tests indicated an abundance of available phosphate, a luxuriant growth of the fungus, with a few exceptions, took place.

A special study was made of calcareous soils. The results are given in table 7. Without any preliminary treatment of soils of pH 7.5 or above, results with the *Cunninghamella* method are usually too low. The agreement of the test with field results was almost perfect for the soils responding to phosphate fertilizer, but only about 50 per cent for the calcareous soils not responding. When these soils are first neutralized with acid, as previously described, the agreement becomes quite satisfactory except with soils 114, 115, 125, 126, and 132. However, the subsoils of Nos. 114 and 115 as tested with the *Cunninghamella* method are well supplied with available phosphorus, and this probably explains why alfalfa grown on these soils does not respond to phosphorus fertilization. Soils 125, 126, and 132 come from areas of limited

moisture, and that may explain the lack of response to phosphate fertilization in the field.

TABLE 7

Phosphate needs of calcareous soils as revealed by Cunninghamella, *chemical, and field tests*

SOIL NUMBER	SOIL REACTION	$CaCO_3$ CONTENT OF SOIL	AMOUNT OF AVAILABLE PHOSPHORUS BY TRUOG CHEMICAL METHOD	CUNNINGHAMELLA METHOD			FIELD TEST RESPONSE TO PHOSPHATE
				Soil not treated	Soil neutralized with citric acid		
				Diameter of lateral growth	Diameter of lateral growth	Amount of available phosphorus by curve interpolation	
	pH	*per cent*	*p.p.m.*	*mm.*	*mm.*	*p.p.m.*	
101	8.4	2.15	12	3	6	4.5	Very good
102	8.1	25.35	6	5	9	7.0	Very good
103	8.4	1.78	70	5	9	7.0	Good
104	7.5	0.16	130	4	10	8.0	Good
105	8.5	6.52	8	3	8	6.0	Very good
106	7.5	0.49	80	4	8	6.0	Very good
107	8.6	8.34	8	3	10	8.0	Very good
108	8.5	1.82	14	6	8	6.0	Good
109	7.6	1.22	56	4	13	11.5	Good
110	8.1	2.31	64	6	12	10.5	Good
111	7.9	2.51	60	6	8	6.0	Good
112	8.1	4.46	30	5	10	8.0	Very good
113	8.0	2.03	26	8	27	31.5	None
114	8.3	3.89	18	8	20	20.0	None
115	7.5	0.28	53	8	18	17.5	None
116	7.8	0.65	92	7	29	35.0	None
117	8.2	4.54	106	5	30	37.0	None
118	8.2	7.00	290	6	52	100.0+	None
119	7.7	0.61	124	14	38	53.0	None
120	7.5	0.12	64	15	38	53.0	None
121	7.9	3.77	62	21	40	58.0	None
122	7.5	0.28	106	20	48	91.0	None
123	7.5	0.46	100	25	50	100.0+	None
124	7.4	0.08	68	37	40	58.0	None
125	8.0	2.34	26	..	12	10.5	None
126	8.1	9.80	5	..	11	9.5	None
127	7.5	0.41	112	..	50	100.0+	None
128	8.1	5.50	82	..	16	15.0	Little
129	8.9	7.90	45	..	7	5.5	.....
130	8.0	0.45	120	..	23	25.0	None
131	8.0	0.35	112	..	42	64.0	None
132	7.9	2.10	19	..	9	7.0	None

Results of the *Cunninghamella* test on 20 soils are compared with those of Mitscherlich's pot test on these soils in table 8. With the exception of soil 136, in which case the result with *Cunninghamella* is a little too high, the results compare favorably.

Practical application

The test using the fungus *Cunninghamella* for determining the phosphate needs of soils should find ready application, because of its simplicity, inexpensiveness, and reliability. The test may be made in any place where a room for incubation is at hand in which the temperature does not vary too greatly. Satisfactory results for practical purposes may be obtained at incubation temperatures ranging from 27° to 30°C. For experimental work, the temperature should be maintained at 28° to 29°C.

TABLE 8

Correlation of results of Cunninghamella *and Mitscherlich methods*

SOIL NUMBER	CUNNINGHAMELLA METHOD		MITSCHERLICH METHOD		
	Diameter of lateral growth	Amount of available phosphorus by curve interpolation	Amount of available phosphorus	Possible maximum crop yield	Need of phosphorus fertilization
	mm.	*p.p.m.*	*p.p.m.*	*per cent*	
134	6	4.5	5.4	29.2	Great
135	6	4.5	5.4	29.2	Great
136	26	29.5	32.4	87.4	Slight
137	18	17.5	40.7	92.7	Slight
138	19	19.0	43.0	93.7	Slight
139	21	22.0	47.2	95.2	Slight
140	27	31.5	53.6	96.8	No
141	24	26.0	53.6	96.8	No
142	32	41.0	57.8	97.5	No
143	28	33.0	60.4	97.8	No
144	40	58.0	62.1	98.1	No
145	40	58.0	73.0	99.0	No
146	38	53.0	75.0	99.2	No
147	43	67.0	75.0	99.2	No
148	25	28.0	79.5	99.4	No
149	24	26.0	82.3	99.6	No
150	22	23.0	94.3	99.7	No
151	50	100.0+	94.3	99.7	No
152	44	71.0	94.3	99.7	No
153	26	29.5	107.2	99.9	No

SUMMARY

A new simple biological soil plaque test, utilizing the fungus *Cunninghamella*, has been developed for measuring the phosphate needs of a soil. In making the test, the soil is moistened with a phosphorus-free nutrient solution and made into a plaque in a small Petri dish. One drop of the spore suspension is placed centrally on the surface. After incubation for about 48 hours, a colony develops, the diameter of which is closely proportional to the amount of available phosphorus present. In developing this test, a large number of

plaque tests were made with about 15 representative molds including several species of *Cunninghamella*. The influence of reaction, kind of nutrient solution, salt content, and supply of available phosphate was investigated. As a result of these studies, the fungus *Cunninghamella* sp. was chosen because of its sensitivity to a lack of, and marked progressive response to an increasing supply of, available phosphate. The test was compared with two *A. niger* methods, a chemical method, field tests, and Mitscherlich's method. The results obtained with many soils from widely separated areas show good agreement with field results. The test seems to work well with the calcareous soils that give great difficulty with some of the other methods.

REFERENCES

(1) BREAZEALE, J. F., AND BURGESS, P. S. 1926 The availability of phosphates in calcareous or alkaline soils. *Ariz. Agr. Exp. Sta. Tech. Bul.* 10: 209–237.

(2) BREAZEALE, J. F., AND MCGEORGE, W. T. 1932 Nutritional disorders in alkaline soils as caused by deficiency of carbon dioxide. *Ariz. Agr. Exp. Sta. Tech. Bul. 41*: 113–153.

(3) LESCH, W. 1933 Beitrag zur Kenntnis des Einflusses des Kalkzustandes eines Bodens auf die Aufnahmefähigkeit der Pflanzen für Phosphorsäure und Kali. *Ztschr. Pflanzenernähr., Düngung, u. Bodenk.* (A) 32: 20–32.

(4) MEHLICH, A., TRUOG, E., AND FRED, E. B. 1933 The *Aspergillus niger* method of measuring available potassium in soil. *Soil Sci.* 35: 259–279.

(5) MITSCHERLICH, E. A. 1930 Die Bestimmung des Düngerbedürfnisses des Bodens. P. Parey, Berlin.

(6) NIKLAS, H., POSCHENRIEDER, H., AND TRISCHLER, J. 1930 Die Kultur des Schimmelpilzes *Aspergillus niger* zur biochemischen Bestimmung der Kali- und Phosphorsäuredüngebedürftigkeit der Böden. *Ernähr. Pflanze* 26: 97–103.

(7) NIKLAS, H., POSCHENRIEDER, H., AND TRISCHLER, J. 1931 Eine neue mikrobiologische Methode zur Feststellung der Düngebedürfigkeit der Böden. *Arch. Pflanzenbau* 5: 451–485.

(8) NIKLAS, H., VILSMEIER, G., AND KOHL, F. 1933 Die Bestimmung der Phosphorsäuredüngebedürftigkeit der Böden mittels *Aspergillus niger. Ztschr. Pflanzenernähr. Düngung u. Bodenk.* (A) 32: 50–70.

(9) SIMAKOVA, T., AND BOVSCHIK, G. 1932 Ueber die mikrobiologische Methode zur Bestimmung des Phosphorbedürfnisses des Bodens mittels *Aspergillus niger. Ztschr. Pflanzenernähr. Düngung, u. Bodenk.* (A) 24: 341–353.

(10) STEWART, R. 1932 The Mitscherlich, Wiessmann and Neubauer methods of determining the nutrient content of soils. *Imp. Bur. Soil Sci. Tech. Comm.* (London) 25: 46 pp.

(11) TRUOG, E. 1930 The determination of the readily available phosphorus of soils. *Jour. Amer. Soc. Agron.* 22: 874–882.

PLATE 1

PLATE 1

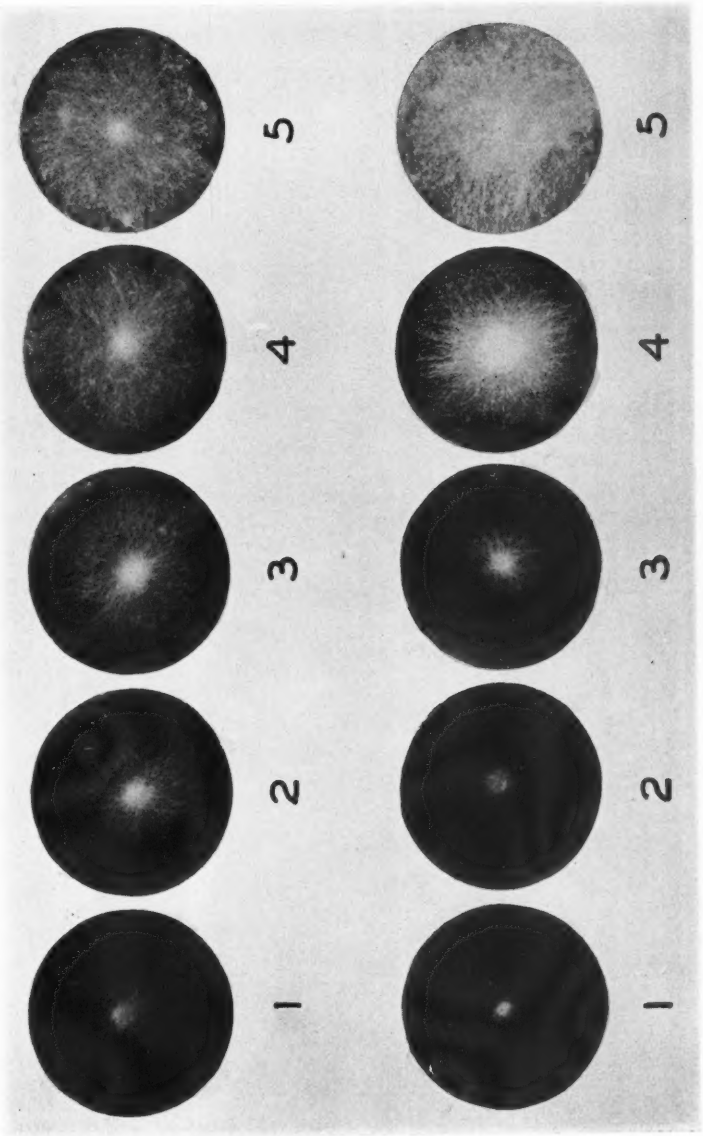
GROWTH OF CUNNINGHAMELLA ON SOILS WITH DIFFERENT AMOUNTS OF AVAILABLE PHOSPHORUS

Upper row: A soil containing 12 p.p.m. available phosphorus and treated with the following increasing amounts of soluble phosphorus:

No. 1— 0 p.p.m.
No. 2—20 p.p.m.
No. 3—40 p.p.m.
No. 4—60 p.p.m.
No. 5—80 p.p.m.

Lower row: Soils, untreated, containing the following amounts of available phosphorus, as revealed by chemical method:

No. 1 contains	4 p.p.m.	Responds markedly to phosphate in the field.
No. 2 contains	12 p.p.m.	Responds markedly to phosphate in the field.
No. 3 contains	17 p.p.m.	Responds moderately to phosphate in the field.
No. 4 contains	64 p.p.m.	No response to phosphate in the field.
No. 5 contains	152 p.p.m.	No response to phosphate in the field.


5
4
3
2
1
5
4
3
2
1

EFFECT OF THE DEGREE OF BASE SATURATION OF A SOIL ON ITS CAPACITY TO FIX PHOSPHORUS IN DIFFICULTLY AVAILABLE FORM[1]

A. FLOYD HECK[2]

Wisconsin Agricultural Experiment Station

Received for publication January 31, 1934

Soils well supplied with lime and not more than slightly acid have been found less frequently deficient in readily available phosphorus than have more acid soils. The effect of the calcium on the mass action equilibrium with phosphorus and also the effect of the higher pH value on the relative solubilities of phosphates (2) are perhaps, largely responsible for this tendency. In the same way, the amount of active or replaceable calcium affects the equilibrium which governs the fixation of applied phosphorus in a difficultly available form. Soils from which the exchangeable bases have been removed fix more phosphorus in difficultly available form, and the increase is somewhat in proportion to the bases removed. The effect of the degree of base saturation in two widely different soils has been studied in its relation to the fixation of phosphorus and is herein reported. In this paper, "phosphorus fixation" will be understood to mean the change from the quickly or readily available form to the slowly or difficultly available forms or to forms very slightly soluble in sulfuric acid of pH 3.

EXPERIMENTAL

The soils used for this study were Miami silt loam, a glaciated timber soil from Wisconsin, and a Hawaiian laterite from the Waipio Substation, Experiment Station of the Hawaiian Sugar Planters' Association. From its colloidal content, this laterite might be characterized as a clay or clay loam, but because of its lateritic characters its physical properties in the field would probably place it in the loam class.

Portions of each soil were entirely unsaturated and other portions saturated to various degrees with calcium. Unsaturation was accomplished by leaching out all replaceable bases with 0.1*N* acetic acid. The saturated condition was obtained by leaching the soil with 0.5*N* neutral calcium acetate solution; and the partially saturated condition, by leaching calcium saturated 40-gm. samples with carbonated water in amounts varying from 50 to 4,000 cc. The

[1] Contribution from the department of soils, University of Wisconsin, Madison, Wisconsin. Published with the permission of the director of the Wisconsin Agricultural Experiment Station.

[2] The writer is appreciative of the kindly coöperation of Prof. E. Truog.

soils were then dried and pulverized, and the capacity of each to fix applied phosphorus was determined.

In view of the fact that a soil is theoretically saturated only when a pH value of 14 is reached, it will be necessary for the discussion in this paper to define "saturation" as that state of base saturation obtained by leaching the soil with 0.5*N* neutral calcium acetate solution. This state of base saturation will be considered as 100 per cent saturation, and all partial saturations will be based thereon.

The pH values were determined by means of the hydrogen electrode and checked by Truog's colorimetric method (Truog soil reaction tester). The

TABLE 1

The relation of base saturation and pH value of Miami silt loam and Waipio soil to their capacities to fix phosphorus in difficultly available form

SOIL TREATMENT	MIAMI SILT LOAM			WAIPIO SOIL		
	Calcium in exchange	pH value	Capacity to fix phosphorus	Calcium in exchange	pH value	Capacity to fix phosphorus
	m.e.		*per cent*	*m.e.*		*per cent*
Original soil, untreated	8.20*	5.94	25.0	15.40†	6.74	67.0
Soil saturated with calcium	11.37	7.20	22.5	19.50	8.03	62.5
Ca-saturated soil leached 50 cc. CO_2-water	9.91	6.02	23.7	17.15	7.55	62.0
" " " " 100 cc. " "	9.22	5.50	27.5	14.25	6.84	64.7
" " " " 200 cc. " "	8.37	5.10	32.5	11.85	6.22	70.5
" " " " 500 cc. " "	7.10	4.80	36.7	9.50	5.55	76.2
" " " " 1,000 cc. " "	5.69	4.45	41.0	7.05	5.09	80.0
" " " " 2,000 cc. " "	4.69	4.20	43.0	4.10	4.67	80.0
" " " " 4,000 cc. " "	3.90	3.80	45.0	1.80	4.24	81.2
Soil saturated with hydrogen	0.00	3.55	45.0	0.00	3.87	82.7

* Total exchangeable bases including 6.45 m.e. of calcium.

† Total exchangeable bases including 8.25 m.e. of calcium and 6.3 m.e. of magnesium.

capacity of the soil to fix phosphorus in difficultly available form was determined by a method proposed by the writer (3) after an application of 400 p.p.m. of phosphorus in solution.

The data for both soils are given in table 1, and include the exchangeable calcium, the pH values, and the capacity of each soil to fix phosphorus in difficultly available form, both before and after the treatment to vary the content of exchangeable calcium.

Relation of hydrogen-ion concentration to the fixation of phosphorus. If the pH values of either of these soils are converted into hydrogen-ion concentrations and the phosphorus fixation percentages are plotted against these values, curves are obtained like that for the Miami silt loam shown in figure 1. This

figure shows that the rate of increase in the capacity of a soil to fix phosphorus in difficultly available form is greatest for any given increment of hydrogen-ion concentration in the range from 0.01×10^{-5} to 0.50×10^{-5}. Above a hydrogen-ion concentration of 1×10^{-5} (pH 5), the increment of fixation drops off very rapidly, and above 6×10^{-5} there is very little further increase in fixation. Figure 1 indicates that although the total may be greater, the

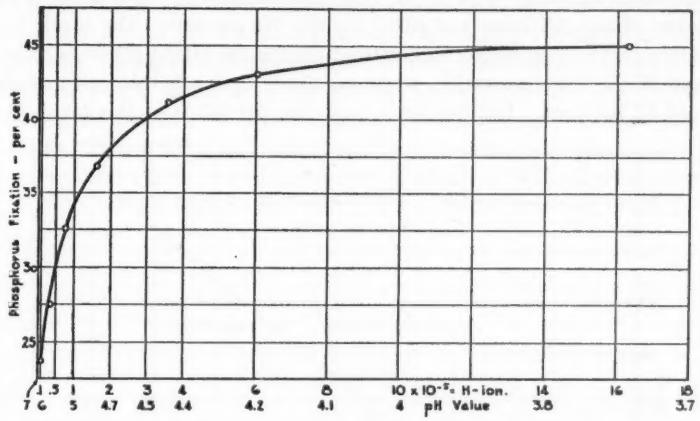


FIG. 1. THE RELATION OF HYDROGEN-ION CONCENTRATION TO PHOSPHORUS FIXATION IN MIAMI SILT LOAM

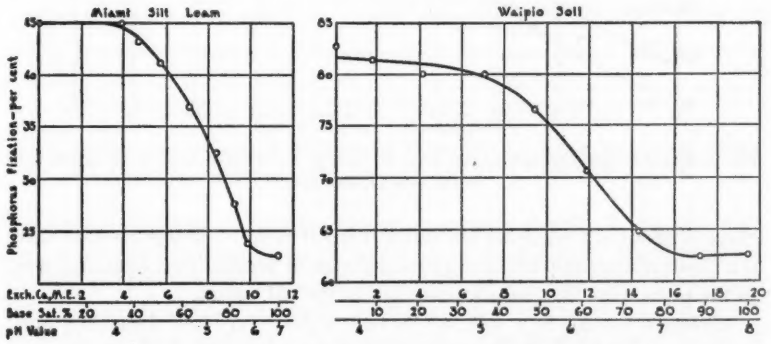

Miami Silt Loam
Waipio Soil
Phosphorus fixation-per cent
Exch. Ca, M.E. 2 4 6 8 10 12
Base Sat. % 20 40 60 80 100
pH Value 4 5 6 7
2 4 6 8 10 12 14 16 18 20
10 20 30 40 50 60 70 80 90 100
4 5 6 7 8

FIG. 2. THE RELATION OF EXCHANGEABLE CALCIUM TO PHOSPHORUS FIXATION

rate of reduction of the capacity of a soil to fix phosphorus in difficultly available form is much more rapid after the pH value of the soil is raised above 5. This same relation also holds true for the Waipio soil.

Relation of exchangeable calcium to phosphorus fixation. If the fixation capacities expressed in percentages of the applied phosphorus fixed in difficultly available form for these two soils are plotted against the milliequivalents of

exchangeable calcium present, there are two breaks in each curve. One break comes near the upper limit of base saturation, above which there is little decrease in fixation, and the other comes toward the lower end of the saturation scale, below which there is little increase in the fixation of phosphorus. These relations for Miami silt loam and the Waipio soil are shown in figure 2. For both soils, the break in the fixation curve at the lower saturations comes at about 30 to 35 per cent base saturation. This is about pH 4 for the Miami silt loam and pH 5 for the Waipio soil. The break in the fixation curve at the higher base saturations for the Miami silt loam comes at about 92 per cent saturation, while for the Waipio soil this value drops to about 82 per cent. For the former soil, the pH value at this break in the

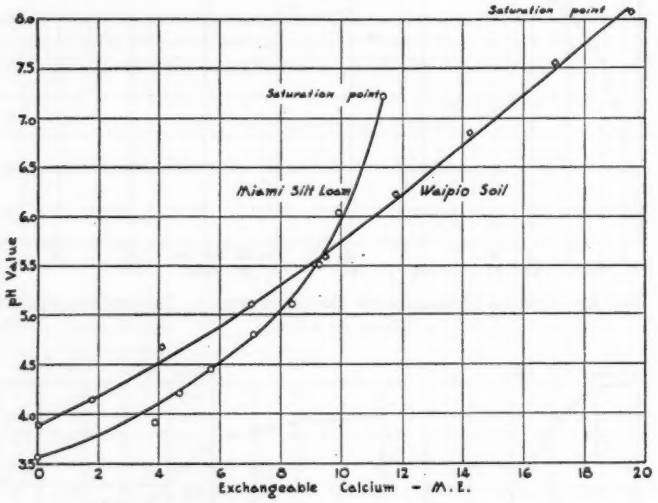


FIG. 3. RELATION OF EXCHANGEABLE BASE (CALCIUM) TO THE pH VALUES OF MIAMI SILT LOAM AND WAIPIO SOIL

curve is about 6.3, while for the latter it is 7.0 to 7.3. It appears that there is a closer relationship of the upper and the lower breaks in the fixation curves to the percentage base saturations than to the pH values.

Minimum fixation in a soil may be very high or very low, depending upon the nature of the soil, but it is not attained at less than 80 to 90 per cent base saturation. In a soil of normal organic content, 90 per cent base saturation will produce a pH value of about 6.3 to 6.5. This correlates with the work of Gaarder (2) in which he has shown that the minimum solubility of phosphorus from calcium phosphate is obtained at pH 6.5 to 7.0. According to his work, at this pH value the phosphorus from calcium phosphate has a solubility of only one-third to one-fourth that of aluminum or iron phosphate.

The shapes of the fixation curves for these two soils differ somewhat, but

the outstanding difference is the pH value at the breaking point of minimum fixation. This difference in the pH value at the breaking point of minimum fixation for the two curves is probably due, in a small part, to the difference in the exchange capacities but, for the most part, to the nature of the exchange materials of these two soils. In figure 3, the pH values for each soil are plotted against the corresponding values for exchangeable calcium, and the resulting curves indicate that the two soils are vastly different in this relationship. The curve for the Waipio soil is nearly a straight line, which indicates the presence, perhaps to a large extent, of only a single exchange complex. In case of the Miami silt loam, there appears to be more than one complex, suggesting the presence of both the organic and the inorganic forms of this substance. This is in accord with the work of Mitchell (6), who reported a high proportion of the organic exchange material in both Carrington and

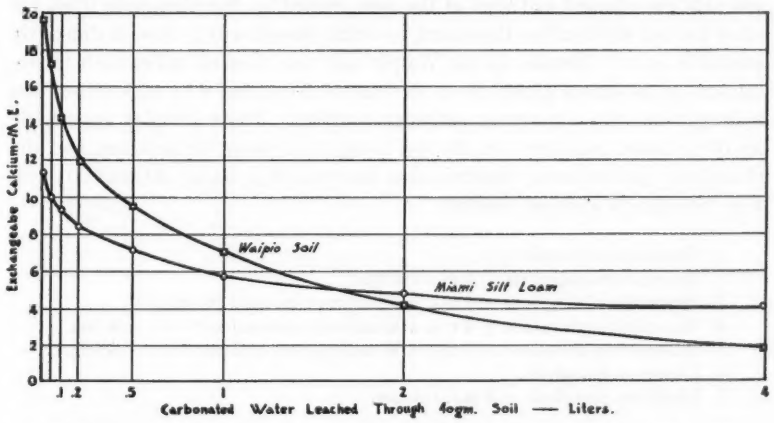


FIG. 4. EXCHANGEABLE CALCIUM RETAINED BY MIAMI SILT LOAM AND WAIPIO SOIL WHEN THE CALCIUM SATURATED SOILS ARE LEACHED WITH CARBONATED WATER

Dodgeville silt loams. Since the inorganic exchange complex is thought to be monobasic and the organic form either dibasic or tetrabasic (4), the chances are that the avidity of these two acids will not be the same and that the organic form will tend to have the greater avidity, which would result in a lower pH value for the same percentage base saturation. The leaching curves in figure 4 indicate that Miami silt loam loses its exchange calcium less readily when leached with carbonated water. This fact, together with the fact that 92 per cent base saturation for Miami silt loam gives a pH value of approximately 6.5 whereas the same base saturation for the Waipio soil gives a pH value of about 7.7, indicates a greater avidity for the acid organic exchange material of the Miami silt loam. This may partially explain why the pH values at minimum fixation for these two soils differ so widely and seem inconsistent with the degree of base saturation at this point.

Although the capacity of the Miami silt loam to fix phosphorus may be relatively low and that for the Waipio soil relatively high, the spread between the maximum and minimum fixation in the two soils is about the same—22.5 per cent for the former and 20 per cent for the latter. The spread between the maximum and minimum fixation percentages for any soil due to variation in base saturation, may perhaps run as high as 30 per cent but seldom runs more than this. Ford (1) has shown that by using an excess of lime on some soils the fixation in difficultly available form may be reduced to a very small amount, but this excess of lime is so large that its use is not practical in the field either from the standpoint of cost or from the difficulty arising from overliming (5).

Other factors related to base saturation and fixation. The amount of exchange material present in a soil, the extent to which the soil is saturated with bases, and also the amount and kind of the base carried by the phosphate itself are other factors which affect the extent to which phosphorus is fixed in difficultly available form. Samples of the Waipio soil were treated either with monocalcium or tricalcium phosphate in various combinations with calcium and the hydrogen saturated inorganic exchange complex. These samples were made up to optimum moisture and allowed to stand at room temperature, and the phosphate fixation being determined at intervals of 2, 10, 20, 40, and 80 days. The treatments were as follows:

1. Monocalcium phosphate.
2. Monocalcium phosphate + 4 m.e. calcium.
3. Monocalcium phosphate + 4 m.e. acid exchange material (inorganic).
4. Monocalcium phosphate + 4 m.e. acid exchange material and 4 m.e. calcium.
5. Monocalcium phosphate + 4 m.e. acid exchange material and 8 m.e. calcium.
6. Tricalcium phosphate.
7. Tricalcium phosphate + 4 m.e. calcium.

Since this soil lacked just 4 m.e. of being saturated with base, the addition of this amount just saturated the exchange to pH 7. This was added as calcium hydroxide in solution. Figure 5 shows how each of these treatments affects the recovery of applied phosphorus in readily available form. It is understood that the phosphorus not recovered in readily available form was fixed in difficultly available form.

When monocalcium phosphate is applied to this soil, the amount that may be recovered in readily available form drops off very rapidly at first and then more slowly later until at the end of 80 days only about 25 per cent in still readily available (curve 1). If the 4 m.e. of replaceable hydrogen in this soil is replaced with calcium (curve 2), the recovery curve runs a few per cent higher and practically parallel with curve 1. Now if 4 m.e. of hydrogen saturated inorganic exchange material is added (curve 3), the curve drops below that for the soil treated with the monocalcium phosphate alone but is still parallel with it. With the addition of 4 m.e. of calcium (curve 4) to a

soil treated as is soil 3, the recovery is greater at first but finally drops and coincides with curve 3. This treatment supplied only half enough calcium to displace the replaceable hydrogen, but when 8 m.e. of calcium is added (curve 5), or enough to completely saturate the exchange with calcium, the recovery is raised to about 42 per cent at 80 days. This indicates that as the amount of exchange material is increased, the exchangeable bases must also be increased in order to maintain or increase the recovery of applied soluble phosphorus in readily available form. However, other factors being equal, an increase in the exchange capacity of a soil accompanied by an 80 to 90 per cent base saturation tends to raise the recovery and lower the fixation of applied soluble phosphate.

Although the fixation curves for the mono- and tricalcium phosphate are practically parallel after the first day, the initial fixation is 20 per cent less for

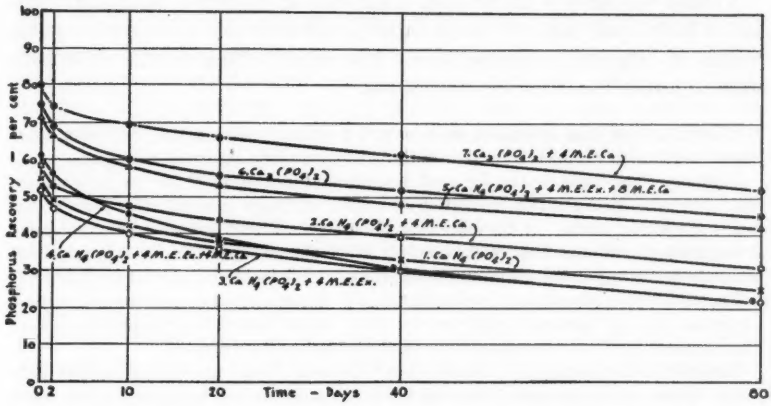


FIG. 5. THE EFFECT OF EXCHANGEABLE CALCIUM AND EXCHANGE MATERIAL ON THE RECOVERY IN READILY AVAILABLE FORM OF PHOSPHORUS APPLIED TO WAIPIO SOIL

the tricalcium form. When the exchange is saturated with calcium, the increase from this saturation in the recovery of applied soluble phosphate is even greater from the tricalcium than from the monocalcium form. Both the solubility of the phosphate and the amount of calcium present seem to affect the fixation equilibrium, and the more calcium present the greater is the tendency for the phosphorus to be held in the calcium form, which results in a lower initial fixation.

DISCUSSION

The maximum change in extent of phosphorus fixation that may be effected by a change in the degree of base saturation is seldom more than 30 per cent and usually not more than 20 per cent of the applied phosphorus. High and low fixing soils are affected to about the same extent. In a soil fixing 35 per

cent, the fixation would be reduced to 10 or 15 per cent by sufficient base saturation, whereas a soil having a 75 per cent maximum fixation would still fix over 50 per cent of the applied phosphorus in difficultly available form.

In high fixing soils that are rather acid, a small field application of lime may even double the availability of the applied phosphorus. If such a soil, fixing 90 per cent of the applied phosphorus, is limed sufficiently to raise the pH value to 5.0 to 5.4, the fixation may be reduced to 80 per cent, which would double the amount of readily available phosphorus from applied superphosphate. With a crop like potatoes, where it is not advisable to raise the pH value above 5.0 to 5.2, there are indications that just such an effect is produced in the field on this type of soil.

SUMMARY

A study was made of the relation of the base saturation of Miami silt loam and of Waipio soil (laterite) to the capacities of these soils to fix applied phosphorus in difficultly available form. The results obtained with these soils seem to justify the following conclusions:

A low degree of base saturation tends to give a soil a greater capacity for fixing phosphorus in difficultly available form than if the soil is more fully saturated with bases.

Minimum phosphorus fixation for a soil is attained at from 80 to 90 per cent base saturation. For soils having a fair proportion of organic exchange material, this point comes toward the higher value. At the same time, these soils will tend to have a lower pH value at the point of minimum fixation than soils in which the exchange complex is largely inorganic; the breaking point of the former being near 6.3, while for the latter it is from 7.0 to 7.5.

The variation in phosphorus fixation that may be brought about by a change in the base saturation of a soil does not usually exceed 20 to 30 per cent of the phosphorus applied. There appears to be little difference in this spread for high or low fixing soils.

Increased exchange capacity of a soil tends to decrease phosphorus fixation, provided the proper degree of base saturation is maintained. If sufficient base saturation is not maintained, increased exchange capacity tends to increase the capacity of a soil to fix phosphorus in difficultly available form.

REFERENCES

(1) Ford, M. C. 1933 The nature of phosphate fixation in soils. *Jour. Amer. Soc. Agron.* 25: 134–144.

(2) Gaarder, T. 1930 Die Bindung der Phosphorsäure im Erdboden. Vestlandets Forstl. Forsøkssta. Meddel. 14.

(3) Heck, A. Floyd 1934 A method for determining the capacity of a soil to fix phosphorus in difficultly available form. *Soil Sci.* 37: 477–482.

(4) McGeorge, W. T. 1931 Organic compounds associated with base exchange reactions in soils. Ariz. Agr. Exp. Sta. Tech. Bul. 31.

(5) Midgley, A. R. 1932 Overliming acid soils. *Jour. Amer. Soc. Agron.* 24: 822–836.

(6) Mitchell, J. 1932 The origin, nature, and importance of soil organic constituents having base exchange properties. *Jour. Amer. Soc. Agron.* 24: 256–275.

THE SOLUBILITY OF PHOSPHORUS IN SOILS FROM SOME ILLINOIS EXPERIMENT FIELDS

H. J. SNIDER

Illinois Agricultural Experiment Station[1]

Received for publication January 15, 1934

The fact that certain soils respond to phosphate treatment and others do not has long been observed in field tests. This difference has been attributed to various causes. It has often been assumed that soils containing an abundant supply of total phosphorus would show little if any response to phosphorus fertilization, whereas, on the other hand, soils with a low content of total phosphorus would respond sharply to such treatment. Many exceptions, however, are found to this expected behavior, and it is quite apparent that response to phosphorus treatment is not necessarily dependent upon the total phosphorus content of soils.

It has been pointed out that soils vary in their power to fix phosphorus, and it is known that fixation by the soil renders the phosphorus less available to plants. Some years ago Stoddard (11) called attention to the possibilities of iron and aluminum compounds fixing phosphates in acid soils. Fraps (9, 10) in reporting his experiments pointed out that as larger amounts of iron and aluminum oxides were found in soils the amount of phosphorus fixed by the soils increased. Comber (5) comments on the fixing of phosphates by iron, aluminum, and calcium. Doughty (6), working with peat soils, states that iron, aluminum, and calcium will account for the fixation of phosphates under field conditions. Teakle (12) shows the possibility that iron, aluminum, manganese, and calcium fix phosphorus. Truog (16) states that yellow-colored soils fix phosphorus more readily than do red-colored soils, because of a difference in the form of iron compounds in these soils. He states further that phosphorus becomes less available, as a result of the interaction of soil phosphates with hydrated iron oxides, forming basic iron phosphates.

PLAN OF THE PRESENT STUDY

An opportunity to study this problem further is afforded by the several soil experiment fields conducted by the University of Illinois in various parts of the state, and the following observations are presented as the record of such a study on a number of these fields. The fields studied represent a number

[1] Contribution from the department of agronomy. Publication authorized by the director January 10, 1934.

of soil types, and they had been under systems of soil treatment for 15 to 22 years. The method of study involved the following procedure:

A determination of the relative solubility of the native phosphorus in soils from treated and untreated field plots.

A determination of the relative ability of the soils from various fields to fix phosphorus.

A study of the crop response of these soils to phosphorus treatment.

DESCRIPTION OF EXPERIMENT FIELDS

On these fields limestone was applied to certain plots at the rate of 1,000 pounds an acre annually, and was continued at this rate until the total reached 8 to 10 tons an acre. During the last 9 years no limestone was added.

A crop residue treatment consisting of cornstalks and a growth of sweet clover turned under once in the rotation as a green manure has been employed. The sweet clover has made a considerable growth only on the limed plots, except on the Hartsburg field where it produces heavy crops on unlimed soil.

The percentage increase in crop yield due to rock phosphate (table 1) represents the percentage value of the crop increase where rock phosphate was used in addition to crop residues and limestone. The rock phosphate was applied at the annual rate of 500 pounds an acre until a total of 4 tons had been added to the soil. A detailed description of the fields and analyses of the crop yields have been given by Bauer (1, 2, 3, 4).

ANALYTICAL METHODS

The phosphorus solubility determinations were made according to the Truog (14) method using 2 gm. soil to 400 cc. of 0.002 *N* buffered H_2SO_4 with the time of extraction extended to 4 and 5 hours.

The relative fixation of phosphorus was determined by adding in solution 50 ppm. of phosphorus as $CaH_4(PO_4)_2$ to 2 gm. of soil. This was allowed to stand in contact with the soil in an open flask at room temperature for 44 to 48 hours, after which it was extracted by the method already indicated except that the time was shortened to one-half hour. A method similar to this was reported by Doughty (6).

SOLUBILITY AND FIXATION RESULTS

The solubility results in figure 1 and table 1 show a wide variation in the amounts of soluble phosphorus obtained from these soils. In some of the soils the solubility greatly increased as the extraction was continued up to 5 hours, as illustrated in figure 1, whereas in others little or no change in solubility occurred after the first half hour of extraction. This difference in solubility along with the differences in value of crop response to phosphorus treatment serves as a basis for placing the fields in rather well-defined groups with respect to phosphorus availability.

The Lebanon and Hartsburg fields are placed in Group I. These soils show relatively high solubility values, increasing greatly with the length of

TABLE 1

Effect of treatment on the solubility and fixation of phosphorus in soils

GROUP	FIELD AND SOIL TYPE	PLOT TREATMENT	SOLUBLE PHOSPHORUS EXTRACTED IN		PHOSPHORUS FIXED	INCREASE IN YIELD DUE TO ROCK PHOSPHATE
			½ hr.	4 hrs.		
			p.p.m.	*p.p.m.*	*per cent*	*per cent*
I	Hartsburg					
	Grundy clay loam	None	40	120	34	5.0
		R*	44	120	34	
		RL†	55	130	22	
	Lebanon					
	Grundy silt loam	None	13	27	30	6.0
		R	13	30	30	
		RL	25	49	21	
II	Toledo					
	Cisne silt loam	None	8	9	48	−10.9
		R	8	9	48	
		RL	12	17	36	
	Sparta					
	Wynoose silt loam	None	6	7	60	−5.5
		R	6	7	60	
		RL	10	15	40	
	Dixon					
	Muscatine silt loam	None	8	9	48	2.3
		R	8	9	48	
		RL	13	19	38	
	Clayton					
	Grundy silt loam	None	6	7	50	2.9
		R	6	7	50	
		RL	11	17	36	
III	Kewanee					
	Muscatine silt loam	None	6	8	54	12.2
		R	6	8	54	
		RL	10	12	42	
	West Salem					
	Bluford silt loam	None	6	6	56	34.9
		R	6	6	56	
		RL	9	10	44	
	Joliet					
	Clarion silt loam	None	9	9	54	41.1
		R	9	9	54	
		RL	9	12	42	
	Elizabethtown					
	Yellow silt loam	None	6	6	62	60.2
		R	6	6	62	
		RL	6	7	54	

* R—crop residues.

† RL—crop residues and limestone.

time extracted. They have, on the other hand, relatively low fixing values, and they show comparatively low percentage increases in crop yields due to added phosphorus. The limestone treatment on these soils increased the solubility of the native phosphorus and also lowered the percentage phosphorus fixed.

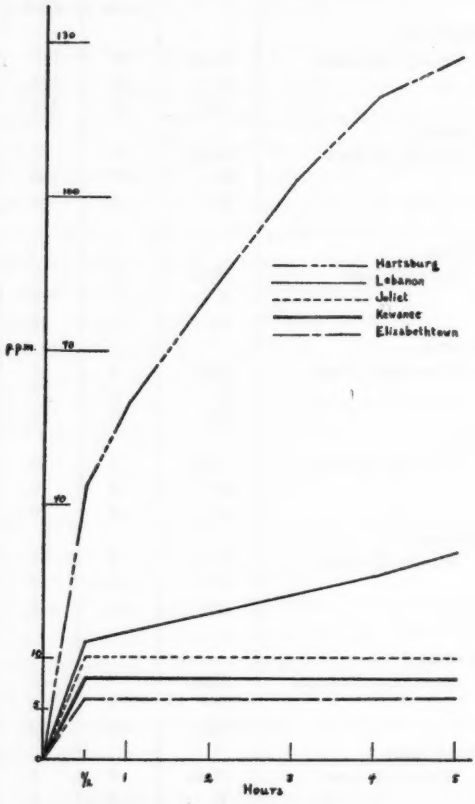


FIG. 1. SOLUBILITY CURVES SHOWING THE EFFECT OF TIME UPON THE AMOUNT OF PHOSPHORUS EXTRACTED FROM DIFFERENT SOILS

From the results given in table 1 it would seem that the soils in Group I are well supplied with available phosphorus which is usable by the growing crop. The addition of rock phosphate to these soils gives only 5 or 6 per cent increases in crop yields.

The Toledo, Sparta, Dixon, and Clayton fields are placed in Group II. These soils show relatively low solubility values on the untreated plots with little or no increase in solubility as the time of extraction was increased up to

4 hours. The soils on these fields have relatively high values for phosphorus fixed and extremely low, or even negative, values for percentage increase in crop yield due to phosphate treatment. The addition of limestone to soils of this group has increased the solubility of the native phosphorus. This greater solubility is more evident when the time of extraction was lengthened to 4 hours.

This increased solubility of the native phosphorus due to the crop residue-limestone treatment apparently made available to the crops sufficient phosphorus to offset the influence of the phosphorus added as rock phosphate.

These results seem to bear out the statement of Ellett (8) that lime acts upon iron compounds in the soil with the effect of making some of the phosphorus available. Truog (13, 15) states that the use of an abundance of lime prevents the interaction of iron oxides with soil phosphates and keeps phosphorus in the form of easily available calcium phosphate.

The Kewanee, West Salem, Joliet, and Elizabethtown fields are placed in Group III. The soils of this group had relatively low solubility values on the untreated plots, as indicated in table 1. The treated soils differed from those of Group II as there was not a large increase in the solubility of the native phosphorus through the influence of the crop residue-limestone treatment.

Apparently there was not sufficient increase in the availability of the native phosphorus caused by the crop residue-lime treatment on these soils to offset the increase in crop yields made by the applied phosphate. The percentages for crop increases in this group ranged from 12.2 up to 60.2 for the phosphorus treatment. This group produced by far the largest increase in crop yield due to applied phosphorus. The percentage phosphorus fixed by the soils of this group was relatively high, and the percentage phosphorus fixed by the soils from the crop residue-lime treatment was higher than that of a similar treatment in the other two groups.

SUMMARY

A study of the availability of phosphorus on a number of the Illinois soil experiment fields has furnished the following information:

The soils studied vary both in solubility of phosphorus and in their power to fix phosphorus.

The solubility and fixation were influenced by the crop residues-limestone treatment.

In general the soils having the lowest relative solubility and the highest relative fixing power gave the greatest response to rock phosphate as measured by increase in crop yields.

The fields studied may be divided into three groups as follows:

a. Those fields representing soils containing a sufficient supply of available native phosphorus so that additional phosphorus applied as a fertilizer is of little value in crop production.

b. Those fields representing soils having a low value for soluble phosphorus on the untreated check plots but with the availability of the native phosphates increased by the crop residue-lime treatment, thus rendering added phosphorus in the form of fertilizer of little value.

c. Those fields representing soils having low availability of phosphorus on the untreated checks but on which the crop residue-lime treatment did not affect the availability of the native phosphorus sufficiently to offset the value of added phosphorus, thus causing the soils of this group to show significant response to phosphorus treatment.

REFERENCES

(1) BAUER, F. C. 1927 Crop yields from Illinois experiment fields. Ill. Agr. Exp. Sta. Bul. 305.

(2) BAUER, F. C. 1930 Crop yields from Illinois experiment fields. Ill. Agr. Exp. Sta. Bul. 370.

(3) BAUER, F. C. 1931 Crop yields from Illinois experiment fields. Ill. Agr. Exp. Sta. Bul. 382.

(4) BAUER, F. C., SMITH, R. S., AND SMITH, L. H. 1926 The Illinois experiment fields. Ill. Agr. Exp. Sta. Bul. 273.

(5) COMBER, N. M. 1924 The rôle of electronegative ions in the reactions between soils and electrolytes. *Trans. Faraday Soc.* 1924: 567–572.

(6) DOUGHTY, J. L. 1930 The fixation of phosphorus by peat soils. *Soil Sci.* 29: 23–35.

(7) DOUGHTY, J. L. 1931 Phosphorus studies of Alberta soils. *Sci. Agr.* 12: 43–51.

(8) ELLETT, W. B. 1910 Lime for Virginia farms. Va. Agr. Exp. Sta. Bul. 187.

(9) FRAPS, G. S. 1909 Active phosphoric acid and its relation to the needs of the soil for phosphoric acid in pot experiments. Tex. Agr. Exp. Sta. Bul. 126.

(10) FRAPS, G. S. 1922 The fixation of phosphoric acid by soils. Tex. Agr. Exp. Sta. Bul. 304.

(11) STODDARD, C. W. 1909 Phosphate availability in its relation to soil acidity. *Wis. Agr. Exp. Sta. Res. Bul.* 2: 50–60.

(12) TEAKLE, L. J. H. 1928 Phosphate in the soil solution as affected by reaction and cation concentration. *Soil Sci.* 25: 143–161.

(13) TRUOG, E. 1916 The utilization of phosphates by agricultural crops including a new theory regarding the feeding power by plants. Wis. Agr. Exp. Sta. Res. Bul. 41.

(14) TRUOG, E. 1930 Determination of the readily available phosphorus of soils. *Jour. Amer. Soc. Agron.* 22: 874–882.

(15) TRUOG, E. 1930 The pH requirement of cultivated plants in natural and artificial cultures. *Amer. Nat.* 64: 300–313.

(16) TRUOG, E., AND FORD, M. C. 1930 New science for an old art. Wis. Agr. Exp. Sta. Bul. 410: 6–8.

A METHOD FOR DETERMINING THE DEGREE OF DECOMPOSITION THAT UNKNOWN DECAYED VEGETABLE ORGANIC MATERIALS HAVE ALREADY UNDERGONE IN NATURE[1]

GEORGE JOHN BOUYOUCOS

Michigan Agricultural Experiment Station

Received for publication December 29, 1933

Although there are methods (3) for following the process of decomposition of organic materials of known state, there is at present no method that can tell quantitatively how far an unknown decayed vegetable material has decomposed. For instance, we cannot take a sample of unknown muck and tell definitely how far this muck has decomposed from the parent material.

The development of the distillation method (1) for determining the amount of combined water and organic matter in soils indicated that the degree of decomposition of unknown decayed organic materials might be determined by the use of high temperature. Accordingly such a method has been developed. It is the object of this paper to present the method and the experimental results obtained through its use. This report is preliminary to a more complete investigation, which is being continued with special effort to perfect further the technique and apparatus.

EXPERIMENTAL

After considerable experimentation, the method finally adopted for determining the degree of decomposition of decayed organic materials is revealed in formulas (A) and (B).

$$\frac{\text{Per cent loss at 310°C. in a bomb}}{\text{Per cent loss on ignition at 550°C. in air}} = \text{Volatilization index} \qquad (A)$$

$$\frac{\text{Volatilization index of fresh material—Volatilization index of unknown decomposed material}}{\text{Volatilization index of fresh material}} \times 100 = \left\{\begin{array}{l}\text{per cent decomposition unknown decayed material has undergone in nature from fresh state}\end{array}\right. \qquad (B)$$

By dividing the per cent of volatile material by the per cent of total loss on ignition, any variation in the ash content of the different organic materials is taken into account. The final results, therefore, are not only comparable but also absolute for the various organic materials.

[1] Journal Article No. 177 (N. S.) from the Michigan Agricultural Experiment Station.

The procedure consists of allowing all the organic materials to become air-dry and grinding them to pass a 2-mm. mesh screen. Exactly 25 or 50 gm. of the air-dry material is placed in a bomb (1) and about 10 gm. in a crucible. The latter sample is used to determine the hygroscopic moisture and the ignition loss of the material. The lid is screwed on the bomb, and the joints are covered with a layer of asbestos cement to insure air-tightness. To take off the cement after heating in the furnace, the cap of the bomb is hit with a hammer and the cement breaks off readily. The process of putting on and taking off this asbestos cement is very simple and requires very little time. The bomb is now placed in an electric muffle at a temperature of 310°C. and allowed to remain for 24 hours. The bomb is then taken out of the muffle furnace and allowed to cool first in the air and finally in a large desiccator. After the bomb is completely cooled, its lid is taken off as described and its contents are poured into a previously weighed receptacle. To be sure that no foreign material will break off from the bomb while it is being emptied of its contents and thus contaminate the latter, cheesecloth is wrapped around the bomb. The contents are weighed on an analytical balance and the percentage of the original material which was volatilized at 310°C. for 24 hours is calculated on the oven-dry basis. To determine the loss on ignition, the material is first dried at 110°C. for 24 hours and then ignited in the muffle furnace at 550°C. for 12 hours. The percentage loss on ignition is then divided into the percentage loss at 310°C., which gives a certain factor or volatilization index for any one material, both in the fresh and decomposed state. Then the difference in the index between the fresh and decomposed state is divided by the index in the fresh state multiplied by 100 and the result is the extent of decomposition that the decayed material has undergone from its fresh state.

The procedure outlined gives very close checks if the temperature at which the materials are heated remains the same. Results show that the volatilization is very sensitive to temperature. If the temperature remains the same, checks will agree within 1 per cent. It is very essential, therefore, that the same temperature within 5°C. be maintained for all materials.

At the temperature of 310°C. the length of time of heating influences the amount of volatilization to a certain extent. Heating a material for 48 hours resulted in about 3 per cent greater loss than heating for 24 hours. At higher temperatures, such as 550°C., all volatilization at that temperature seems to be completed in much shorter periods. Heating the organic materials at higher temperatures such as 550°C. gives a higher volatilization index, but the relationship between the volatilization index of various materials is nearly the same as that which exists when the determinations are made at 310°C. The temperature of 310°C., however, seems to be the best temperature to heat the materials because it is nearer their critical temperature of decomposition, is not too drastic, and is also easier to maintain.

It is essential that the materials be heated in a bomb or in the absence of air, otherwise unequal heating due to premature ignition takes place.

In tables 1 and 2 are presented the experimental results on the volatilization index as obtained by the temperature method on a large number of different representative organic materials in the fresh and decomposed state. Unfortunately, it was very difficult to obtain very good samples of materials in a highly decomposed state other than muck. Nearly all the decayed materials

TABLE 1

Volatilization index of fresh materials heated at 310°C.

MATERIALS	HYGROSCOPIC MOISTURE	LOSS ON IGNITION	LOSS AT 310°C. IN BOMB	VOLATILIZATION INDEX
	per cent	*per cent*	*per cent*	*per cent*
Alfalfa stems	9.46	94.0	54.24	57.6
Alfalfa leaves	8.70	91.0	52.2	57.4
Clover, mature	13.35	94.22	51.11	54.58
Lettuce leaves, green	12.10	84.4	48.1	57.01
Oats, young plants	10.14	92.2	52.1	55.2
Oat straw	9.10	95.8	51.5	53.8
Wheat straw	7.7	96.2	55.18	56.4
Corn, mature stalks	5.8	92.58	53.51	57.6
Alfalfa roots	12.70	95.8	55.1	57.4
Pasture grass, green	9.93	91.80	49.0	53.4
Rye straw	9.80	96.15	51.4	53.4
Filter paper	4.15	99.95	55.94	55.95
Oakwood, sound	8.70	99.85	52.8	52.9
Pine wood, sound	8.66	99.80	53.0	53.05
Wheat flour	10.18	93.00	54.10	58.20
Sphagnum moss	10.20	92.0	47.8	51.9
Sedge	12.22	94.8	50.25	52.90
Wood shavings	8.84	99.5	53.2	53.5
Green water lilies	9.00	92.5	48.43	52.5
Horse manure	3.2	92.3	49.2	53.2
Cow manure	8.24	90.6	46.51	51.23
Oak leaves, mature	9.83	94.0	44.3	47.0
Maple leaves, mature	11.03	91.3	43.8	48.0
Beach leaves, mature	11.12	94.5	45.77	48.5
Pine needles, in fall	7.02	96.7	45.9	47.3
Walnut shells	8.08	99.3	54.8	55.2

were only partially decomposed, and their extent of decay was, of course unknown. In the Tables are also included the data on hygroscopic moisture, loss on ignition, and volatilization loss at 310°C.

Table 1, which contains the data for the fresh materials, shows that, with the exception of the tree leaves, the volatilization index of all fresh materials is not greatly different, ranging only from about 52 to 58 per cent. The most interesting thing is that such fresh materials as walnut shells, pine wood, and

oak wood have a volatilization index only slightly smaller than such fresh materials as alfalfa leaves, lettuce leaves, and wheat flour. The only fresh materials that seem to have decidedly different volatilization indexes from the rest of the fresh materials are the tree leaves. A possible explanation for this variation will be offered subsequently in this paper.

Table 2, which contains the results for the decayed or partially decayed organic materials, shows that their volatilization index varies from 0 to about 40 per cent, which is far below that of the fresh materials. With the exception of coal, mucks seem to have the smallest volatilization index, with the mini-

TABLE 2

Volatilization index of unknown decayed materials heated at 310°C.

MATERIALS	HYGROSCOPIC MOISTURE	LOSS ON IGNITION	LOSS AT 310°C. IN BOMB	VOLATILIZATION INDEX
	per cent	*per cent*	*per cent*	*per cent*
Wheat straw	9.09	84.0	30.5	36.3
Oat straw	9.22	81.2	29.7	36.6
Corn stalks	5.60	76.5	31.0	40.52
Clover	9.53	93.43	27.0	28.8
Wood 1	4.57	97.32	36.81	37.81
Wood 2	5.32	98.95	44.5	44.9
Sedge moss	11.25	95.36	34.2	36.0
Sphagnum moss	13.10	93.10	32.0	34.4
Beach leaves	10.32	60.00	23.36	38.93
Pine needles	13.38	82.20	33.2	40.82
Maple leaves	9.65	84.30	32.8	38.90
Horse manure	7.10	61.7	18.18	30.44
Cow manure	8.05	81.4	32.88	40.4
Raw peat 1	9.42	97.2	38.5	39.6
Raw peat 2	8.32	97.12	37.7	38.8
Peat	12.23	97.90	26.00	33.4
Muck 1	12.47	90.0	20.9	23.3
Muck 2	12.87	79.10	21.78	27.55
Muck 3	11.05	79.8	22.7	28.7
Muck 4	13.15	88.7	20.20	22.8
Pocahontas Coal	0.58	97.5	0.0	0.0

mum around 23 per cent. Peats have a higher volatilization index, with a maximum around 38 per cent.

What is the meaning of the difference in the volatilization indexes between the fresh and decayed organic materials as revealed in tables 1 and 2? The higher volatilization index of the fresh materials over that of the decayed materials simply means that the fresh materials have a high content of easily decomposable substances which are volatilized at the temperature of 310°C., while the decayed materials have a low volatilization index because their easily decomposable substances have already disappeared in the natural de-

composition process and there is left behind a higher content of the resistant substances.

The lower volatilization index of the fresh but mature leaves of trees might be explained somewhat on the same basis as that of decayed materials. Since the leaves serve the purpose of manufacturing the food of the trees, their easily decomposable substances, such as the sugar, are taken away from them by the trees, and as a consequence their composition contains a correspondingly greater proportion of the more resistant substances such as lignin.

TABLE 3

Degree of decomposition unknown decayed materials have already undergone in nature from their original fresh state

MATERIALS	VOLATILIZATION INDEX OF FRESH MATERIAL	VOLATILIZATION INDEX OF DECAYED MATERIAL	DIFFERENCES BETWEEN FRESH AND DECAYED MATERIAL	DEGREE OF DECOMPOSITION DECAYED MATERIALS HAVE UNDERGONE FROM FRESH STATE
	per cent	*per cent*	*per cent*	*per cent*
Wheat straw	56.4	36.3	20.1	35.6
Oat straw	53.8	36.6	17.2	32.0
Corn stalks	57.6	40.5	17.1	29.7
Clover	54.6	28.8	25.8	47.3
Wood	52.9	37.8	15.1	28.5
Sedge moss	52.9	36.0	16.9	31.9
Sphagnum moss	51.9	34.4	17.5	33.7
Beech leaves	48.5	38.9	9.6	19.8
Pine needles	47.3	40.8	6.5	13.7
Maple leaves	48.5	38.9	9.6	19.8
Horse manure	53.2	30.4	22.8	42.9
Cow manure	51.2	40.4	10.8	21.1
Raw peat	53.0*	39.6	13.4	25.3
Muck 1	53.0*	22.8	30.2	57.0
Muck 2	53.0*	27.5	25.5	48.1

* In fresh state.

The products formed both by the destructive distillation at 310°C. and by aerobic fermentation seem to be qualitatively similar; namely, water, carbon dioxide, and ammonia. It remains to be determined whether they are also quantitatively similar. The residual products, such as lignin, also seem to be similar under the two processes.

The data in table 3 reveal a very wide difference in the degree of decomposition that the various unknown decayed organic substances have already undergone from their fresh state. They show for instance that the decayed sample of pine needles used had decayed only 13.7 per cent from the original state, whereas muck had decayed 57 per cent from the fresh parent material. These measurements were obtained according to the formulas already presented.

How closely the indicated degree of decomposition represents the real decomposition that has actually taken place in nature in the various decayed materials cannot, of course, be stated, as there is no way of knowing. The results, however, seem to be reasonable.

SUMMARY

A method, based on volatilization, is presented for determining the degree of decomposition that unknown decayed vegetable organic materials have already undergone in nature from their fresh state.

The method consists of heating the materials in a bomb at 310°C. for 24 hours. The volatilization loss that takes place at this temperature is divided by the ignition loss of the material, and that gives a certain volatilization index.

It is found that the volatilization index of fresh materials is much higher than that of the decayed materials.

It is assumed that this difference in the volatilization index represents degree of decomposition of the decayed materials. When the volatilization index of a certain material in both the fresh and the decayed states is known, the degree of decomposition that the decayed material has already undergone can be ascertained.

By this method it is shown, for instance, that some mucks have already undergone a decomposition of 57 per cent from the original state.

REFERENCES

(1) Bouyoucos, G. J. 1932 A method for determining combined water and organic matter in soils. *Soil Sci.* 34: 259–265.

(2) Hurd, Chas. D. 1929 The Pyrolysis of Carbon Compounds. The Chemical Catalog Company, New York.

(3) Waksman, S. A. 1932 Principles of Soil Microbiology. The Williams & Wilkins Company, Baltimore.

MORPHOLOGY AND GENESIS OF THE SOLONETZ SOILS OF WESTERN NORTH DAKOTA

CHARLES E. KELLOGG[1]

North Dakota Agricultural College

Received for publication January 26, 1934

The prominent feature of the solonetz soils is the presence of sodium among their exchangeable bases. According to the work of K. K. Gedroiz the solonetz soils represent one stage in the evolution of the alkali soils (3). These genetic stages in the evolution of such soils may be summarized as follows:[2]

(*a*) Normal soil (chernozem, brown soil, etc.). In these soils the base exchange is largely saturated with the divalent cations, the colloids are in a flocculated state, and the soil is nearly neutral. The *calcification* process is dominant.

(*b*) Solonchak (saline). In this case there is an excess of soluble salts and usually some portion of the divalent cations have been replaced by monovalent cations, especially sodium. The presence of the excess salts prevents the hydrolysis of the sodium from the exchange and keep the colloids flocculated. The soil is not highly alkaline.[3] This process is best called *salinization.*

(*c*) Solonetz (alkali soil). These soils have a relatively high percentage of exchangeable sodium in the complex and a low percentage of soluble salts. As the drainage of the solonchak becomes improved the excess soluble salts are removed. In such cases where these salts were essentially all divalent the soil changes back to the normal. In most instances, however, the solonchak contains a considerable amount of exchange sodium, such that when the excess salts are removed the colloids are given an increased mobility and the soil becomes highly alkaline as a result of the hydrolysis of the sodium to form sodium hydroxide. (This, of course, passes to sodium carbonate.) Because of the deflocculated state of the colloidal portion, the soil exhibits a prismatic structure with hard aggregates. This process is called *solonization* and might be said to consist of desalinization plus alkalinization.

(*d*) Soloth. As soon as solonetz has formed, the highly dispersed colloids tend to move downward in the solum. In a sense this process is similar to podzolization except that the original mobility of the colloids is due to exchange sodium rather than to exchange hydrogen. The exchange capacity of the soil becomes reduced and the pH becomes lower with an increase in exchangeable hydrogen. A light colored A_2 horizon with a platy structure and a light texture develops over a dark, hard, columnar B_2 horizon. With the completion of the development the B_2 horizon loses its columnar structure and itself becomes somewhat acid. This process is called *solodization.*[4]

---

[1] Now with the Bureau of Chemistry and Soils, U. S. Department of Agriculture, Washington, D. C.

[2] Nikiforoff, C. C. Evolution of the alkali soils; their classification and reclamation. Unpublished manuscript.

[3] Except in the unusual case of flooding with sodium carbonate which has been introduced from a solonetz at a higher level.

[4] This process has been spoken of as the "degradation of the solonetz" but the writer feels that the term "degradation" should be confined to the influence of the podzolization process.

(*e*) Normal soil (chernozem, brown soil, etc.). After the complete formation of soloth with the removal of the mobile colloids, the continued growth of the native grasses again changes the soil to that normal for the region. This process of calcification impinged on the soloth might be called *reconstruction*.

The most common occurrence of the solonchak, and consequently the solonetz and soloth, is as a "complex." Within an area having the normal profile, or nearly such a profile, will be irregular spots of these soils. And these spots will not be uniform in any characteristic. Kelley has presented some interesting data on the irregular nature of alkali soils in California (4). In soil mapping such areas must be classified simply as a complex.

Differences in the solonchak stage will, of course, be reflected in both the solonetz and the soloth. The solonchak may have almost any conceivable ratio of the various cations in the saline waters: hence, depending upon the ratio of divalent to monovalent cations, the resulting solonetz will vary all the way from the normal profile, through a weak solonetz profile, to the extremely hard, prismatic solonetz. These salts may have drenched the soil quite uniformly from the surface, as in a level lake floor, or, as is more generally the case, have risen in irregular patches from the water table. Again the salts, having risen by capillary action with the water, may come to the surface and gives rise to a crust of *puff* at the surface (exterior solonchak), or the capillary movement may have ceased at some depth within the profile, leaving the salts beneath the surface (interior solonchak).

As a further complication, all stages of development between solonchak and soloth may be found. As a matter of fact, one rarely, if ever, finds a solonetz which is not tending either somewhat toward solonchak or toward soloth. As soon as solonetz forms it immediately begins to solotize with the development of a profile approaching the soloth.

SOLONETZ SOILS OF WESTERN NORTH DAKOTA

During the summer of 1931 and subsequently the writer has been much interested in the solonetz-complex of western North Dakota. Large areas in the Great Plains, and extending north into Canada, are characterized by a spotted appearance of the surface. Small, irregular, but roughly elliptical, depressions break the uniformity of the prairie landscape. Such a landscape is perhaps best summarized in the words of Dokuchaev as "smallpox on the face of the steppe" (7). These depressions are usually about 6 to 15 inches in depth and 4 to 15 feet in diameter. They are either barren of vegetation or support a meager growth of xerophytic and halophytic plants. Locally these spots are known as "buffalo wallows" or "slick spots;" and in Canada as "burnouts" (6). When the land is plowed they are evident by their hard, cloddy nature when dry and by extreme stickness when moist.

The solonetz-complex is found on nearly level or gently sloping land, and is developed from a variety of parent materials including glacial till, weathered sandstones and shales, and alluvial deposits. .In cases where this condition

is developed from glacial till, the till is thin over the weathered marine deposits or the till takes the form of a gentle slope away from some higher outcrop of the residual material, the seepage from which may influence the soil on the slope.

GENERAL FEATURES OF THE AREA

The climate is of the extreme continental type with hot summers and cold winters. The annual rainfall varies considerably from a yearly mean of about 15 inches. The general features of importance are shown in figure 1.

The parent material for soil of the northern part is of glacial origin, underlain by marine deposits of sandstone, shale, and clay. In the southern part of western North Dakota the soils are developed directly from this residual

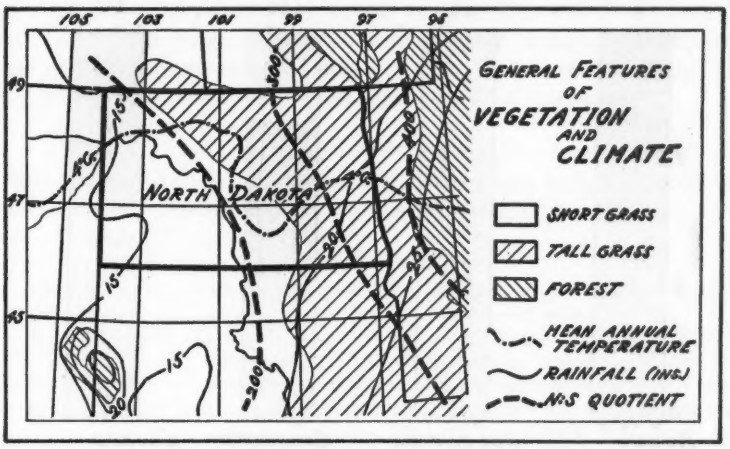


FIG. 1. SKETCH MAP SHOWING THE GENERAL FEATURES OF VEGETATION AND CLIMATE FOR WESTERN NORTH DAKOTA

material. The clayey alluvium of the slopes and valleys frequently gives rise to the solonetz-complex.

The native vegetation consists of the mixed prairie type with such species predominating as grama grass (*Bouteloua gracilis*), needle grasses (*Stipa comata and Stipa viridula*), nigger wool (*Carex filifolia*), June grass (*Koeleria cristata*), western wheat grass (*Agropyron smithii*), and salt grass (*Distichlis spicata*). This last named species is found only on the solonchak and solonetz soils together with salt sage (*Atriplex nuttallii*), cacti (*Opuntia fragilis*), and similar plants.

The normal soil for the area varies from the chestnut brown soils in the neighborhood of the Missouri River at Bismarck to the brown soil near the Montana state line. On the steeper, and consequently drier, slopes sierozems (gray soils) are developed. Many large areas show some definite influence

from sodium but are not sufficiently solonized to be classified as solonetz, although there is a pronounced prismatic structure and a dark brownish-gray color. The dominant profile for the western part of the area is shown in figure 2 and may be illustrated by the profile from Scobey loam, described a little later.

INVESTIGATIONS

This investigation has fallen naturally into two parts: (*a*) The field study of the morphology of the soils, together with observation of the vegetation, relief, and other factors of importance in genesis. Clearly this is the most important phase of a study of this kind. After the examination of a great

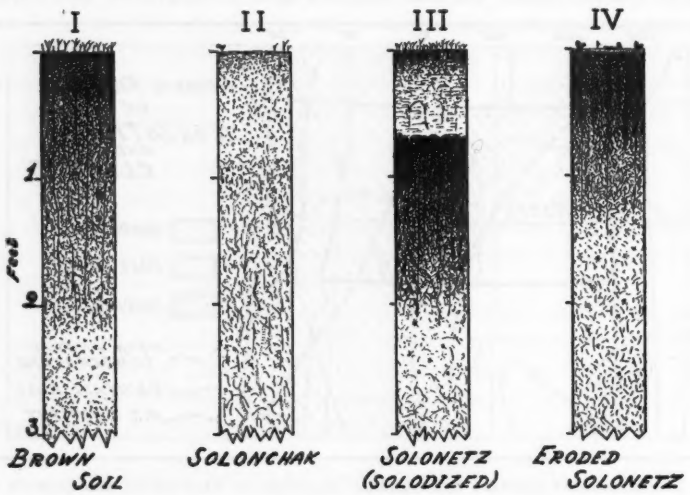


FIG. 2. SKETCHES SHOWING SOME OF THE PRINCIPAL TYPES OF PROFILES MENTIONED IN THE TEXT

many profiles they were classified according to their development, and examples are presented which most nearly approach the average for each class. (*b*) A few laboratory determinations were made in order to throw further light on the more detailed conditions in the soil horizons.

For such an investigation a great many morphological studies were made from excavations in what appeared to be different stages in the development. From a portion of these profiles, samples were collected by horizons for physical and chemical determinations.[5]

Profile descriptions were made in accordance with the uniform method described in detail previously (5).

[5] The writer has been assisted by his students and by workers in the U. S. Bureau of Chemistry and Soils in making the laboratory determinations.

Depression of the freezing point (-d F. P.) has been determined as a measure of the soluble material in the soil according to the general method of Bouyoucos and McCool (2), except that the soil and water are in the ratio of 1:1.

pH was determined in the regular way by use of the hydrogen-electrode. In this case the ratio of soil to water was 1:2½.

Mechanical analysis was determined in all cases, except for the normal profile, by use of the hydrometer method as suggested by Bouyoucos (1) and modified in the Bureau of Public Roads (8, 9).

For the extraction of the exchangeable material in the soil, 20 gm. of soil was treated with 100 cc. of 0.05 *N* HCl plus the HCl-equivalent of carbonates present. Three successive treatments with 50 cc. of HCl were likewise made and filtered, and the material obtained was combined and analyzed. This was followed by a sufficient number of treatments with 50-cc. portions until the residual dry matter amounted to only 5 to 10 mgm. The residues from all these filtrations were combined and analyzed. In table 4, giving the results for solonschak, only a total of 250 cc. of HCl was used.

The Normal Soil

The normal soil for the western part of the area may be illustrated by the following profile from the Scobey loam (see also fig. 2):

*Scobey loam (profile 1)**

A_1†	0 to 1″	Dark grayish brown light loam with soft, fine crumb, mulch-like structure. Thoroughly permeated with roots.
A_2	1 to 4½″	Dark brown loam with soft crumb structure. In place, the soil is fairly platy. The lower part of the horizon grades into the prisms of B_2. This portion of the soil contains many grass roots.
B_2	4½ to 13″	Brown (faintly reddish) sandy clay loam with a very well-developed prismatic structure. These vertical prismatic blocks range from ½ to 1½ inches in diameter. When removed the soil is in vesicular, elongated pieces ranging from small to large nut-size, and held together by grass roots. These pieces are fairly easily crushed to a medium hard crumb. When dry the prisms are noticeably brittle. This layer grades into
B_3	13 to 20″	Brown, with olive-drab tinge, sandy clay loam. The soil has a well-developed prismatic structure, but the vertical prisms and their constituent blocks are somewhat larger than those in B_2 and somewhat less friable. The soil effervesces very mildly with HCl. Roots penetrate the solum with ease, but few go beneath this horizon.
C_1 (Carbonate)	20 to 26″	Light olive-drab, strongly mottled with white, sandy clay till. The soil is compact in place, but removed chunks are easily friable. In the lower part the mottling becomes less intense and the soil grades into
C	26″	Light olive-drab sandy clay till.

* Location: SW¼. SW¼. Section 7, T151N, R100W.

† Horizon nomenclature throughout this paper is according to the method outlined elsewhere (5).

TABLE 1

*Mechanical analysis of Scobey loam, profile 1**

HORIZON	DEPTH	FINE GRAVEL	COARSE SAND	MEDIUM SAND	FINE SAND	VERY FINE SAND	SILT	CLAY	TOTAL	COLLOID	ORGANIC MATTER BY H_2O_2
	inches	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
A_1	0–1	0.6	3.1	6.2	17.2	9.1	37.7	21.0	94.9	16.0	4.6
A_2	1–4½	0.9	3.4	6.8	19.1	9.8	35.2	21.3	96.5	18.4	3.1
B_2	4½–13	0.4	3.2	6.8	20.0	9.8	27.2	30.4	97.8	26.0	1.9
B_3	13–20	0.8	2.6	6.0	15.8	10.2	26.8	36.5	98.8	30.3	1.0
C_1	20–26	0.9	2.2	3.9	10.5	10.0	26.7	44.7	98.9	34.2	0.8
C_2	26+	1.5	2.2	3.7	10.5	10.9	29.8	40.6	99.2	32.2	0.3

* By H. W. Lakin and T. M. Shaw.

TABLE 2

*Total chemical analyses of Scobey loam, profile 1**

HORIZON	DEPTH	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3	IGNITION LOSS	TOTAL	N	ORGANIC MATTER COMBUSTION METHOD	pH	$\frac{-d}{F \cdot P}$
	inches	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*		°C.
A_1	0–1	74.26	0.48	10.84	2.78	0.08	1.43	0.82	2.03	1.11	0.21	0.15	6.71	100.90	0.23	3.71	6.4	0.010
A_2	1–4½	72.66	0.54	12.54	3.09	0.07	1.14	0.78	2.12	1.19	0.16	0.12	5.40	99.81	0.16	2.50	6.3	0.014
B_2	4½–13	73.38	0.54	12.41	3.77	0.06	1.29	1.14	2.10	1.08	0.15	0.11	4.01	100.04	0.10	0.99	6.7	0.004
B_3	13–20	68.14	0.58	13.09	4.52	0.07	2.32	1.69	2.02	0.97	0.22	0.12	6.00	100.74	0.10	1.42	6.85	0.007
C_1	20–26	57.44	0.49	11.38	4.10	0.06	9.77	2.64	1.79	0.91	0.23	0.12	11.89	100.82	0.10	1.32	7.85	0.014
C	26+	58.19	0.56	12.90	4.30	0.07	8.44	3.25	1.99	1.07	0.25	0.14	9.52	100.68	0.04	1.46	7.95	0.010

* Chemical analyses by Mr. G. J. Hough of the Bureau of Chemistry and Soils.

The mechanical and chemical analyses of this profile are shown in tables 1 and 2 respectively. These data show that there likely has been some movement of colloid from the upper to the lower part of the solum.

The Solonchak Stage

Throughout the region under discussion are areas of solonchak, but these are much less numerous at present than the areas of the solonetz-complex. Two profiles from those investigated are herein presented as typical of the solonchak—complex. In figure 3 is shown a cross section made through one of the puffed spots. The most striking feature of such soils is the puffing at the surface in small, irregular spots. In cases where the salty water moves up by capillary action from the water table, as soon as the salt comes in contact with the clay the colloids will become flocculated and capillary activity intensified.

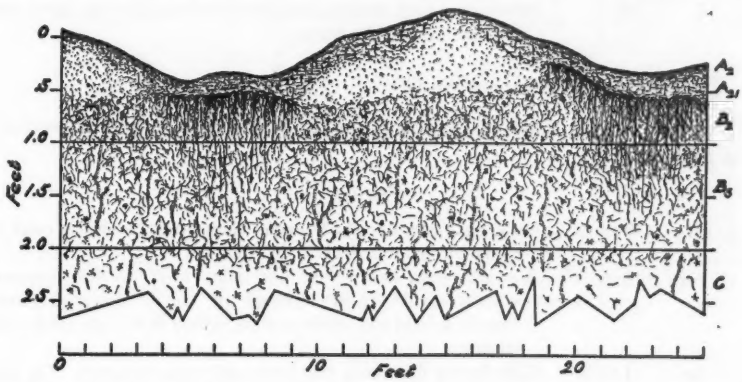


FIG. 3. CROSS SECTION, MADE TO SCALE FROM LEVEL NOTES, THROUGH THE PUFFED SPOT IN THE SOLONCHAK-COMPLEX

Three profiles included in this section are described

In this way any small inequalities in the original material become greatly intensified. Likely one could never expect to find an area of solonchak in which the salts have risen from beneath that would be at all uniform. It is important to note here that the general feature of discontinuity characteristic of most alkali soils in all stages is introduced during the earliest stage of their evolution. These raised, or puffed, spots cover roughly one-half of the area. A picture of this type of landscape is reproduced in plate 1, figure 1.

The profile described in the following is taken through the puffed spot shown in the cross section of figure 3. The soil is developed from alluvium on a stream terrace. The terrace has about 1 per cent of slope toward the stream and away from the adjacent upland. The vegetation on the puffed spots consists of a sparse stand of salt grass, salt sage, Texas crab grass, and

Russian thistle. Between the spots the vegetation is somewhat more dense and includes western wheat grass and a little grama grass.

*Solonchak (profile 3)**

A_3	0 to ¼″	Light gray, light very fine sandy loam. This brittle, vesicular crust is easily crushed to a single grain structure.
A_{21}	¼″ to 2″	Light grayish brown, heavy very fine sandy loam. With difficulty the soil rubs to nearly a single grain. There are a few irregular vertical cracks.
B_1	2 to 9″	Light brown fine sandy clay with a very fluffy, fine crumb structure. When dry many small crystals of salt may be seen.
B_2	9 to 14″	Brownish olive clay with a soft crumb structure, containing noticeable white flecks.
B_3	14 to 30″	Light brownish olive clay, containing many white flecks. The material is soft and friable (flocculated) in place but squeezes into a cheesy mass.
C	30″	Heavy olive clay, massive and plastic in place, but not hard, and contains many white flecks.

* Location: E½, Section 17, T150N, R98W.

Another profile, taken at the margin of the puffed space may be described as follows:

Profile 4

A_2	0 to ½″	Gray, light very fine sandy loam. This brittle, vesicular crust is easily crushed to a single grain structure.
A_{21}	½ to 1″	Brownish gray, heavy very fine sandy loam. A few irregular vertical cracks appear, although the soil is somewhat platy. Pieces are hard and brittle and are rubbed to a single grain with difficulty.
A_{22}	1 to 3″	Light brown fine sandy clay loam with some platiness. The soil is brittle but easily friable to a medium crumb. White flecks appear in the lower part.
		The remainder of the profile is similar to profile 3.

Profile 5

A_2	0 to 1″	Gray fine sandy loam. The soil is brittle and platy but contains more organic matter than the surface layers of the profiles described above.
A_{21}	1 to 3″	Yellowish-brown platy, brittle heavy loam.
B_2	3 to 8″	Dull brown clay with ill-defined prismatic structure. The prisms are hard and finely vesicular; they are crushed with difficulty to angular pea-sized pieces.
B_3	8 to 20″	Light brownish olive clay with a few vertical cracks. The mass has a soft, subangular, pea-sized structure.
		There are many flecks and vertical streaks of salt.
		The remainder of the profile is similar to that described under profile 3.

Table 3 gives data regarding the physical nature of this soil, and table 4 gives data regarding the chemical nature of the material extracted with dilute

HCl. These data clearly show a solonchak which is just beginning to develop into a solonetz. The salts have already left the very upper layers, and the

TABLE 3

Mechanical analyses, pH, and −d F·P of solonchak, profiles 3, 4, and 5

PROFILE NO.	HORIZON	DEPTH	MECHANICAL ANALYSIS*				−d F·P†	pH‡
			Sand above 0.05 mm.	Silt 0.005 to 0.05 mm.	Clay below 0.005 mm.	Fine clay below 0.002 mm.		
		inches	*per cent*	*per cent*	*per cent*	*per cent.*	*°C.*	
3	A_2	0–¼	..	..	..	..	0.039	8.9
	A_{21}	¼–2	..	..	..	..	0.012	9.05
	B_1	2–9	37	33	30	18	0.466	9.1
	B_2	9–14	31	34	35	25	0.510	9.1
	B_3	14–30	27	36	37	27	0.504	9.3
	C	30+	29	42	29	21	0.471	9.15
4	A_2	0–½	43	47	10	7	0.022	8.8
	A_{21}	½–1	47	33	20	14	0.044	9.3
	A_{22}	1–3	..	..	..	..	0.233	8.75
5	A_2	0–1	40	39	21	15	0.002	8.1
	A_{21}	1–3	35	42	23	16	0.020	8.0
	B_2	3–8	36	33	31	24.5	0.057	9.4
	B_3	8–20	25.5	30.5	44	34	0.320	9.05

* By the hydrometer method, as modified in the Bureau of Public Roads (8, 9).

† For the depression of the freezing point, ratio of soil and water, 1:1.

‡ By the hydrogen electrode.

TABLE 4

Exchange material extracted from solonchak, profiles 3 and 4 by treatment with 0.05 N HCl†*

(m.e. per 100 gm. soil)

HORIZON	PROFILE NO.	DEPTH	SiO_2	Al_2O_3	MnO	CaO	MgO	K_2O	Na_2O	TOTAL
		inches								
A_2 (crust)	3	0–¼	1.36	5.94	0.25	22.95	16.90	0.25	1.51	49.16
A_{21}		¼–2	1.86	4.71	0.25	20.80	18.60	0.24	3.83	50.29
B_1		2–9	1.19	3.88	0.17	45.50	16.30	0.24	11.00	78.28
A_2 (crust)	4	0–½	1.42	5.12	0.29	23.92	17.10	0.25	1.16	49.26
A_{21}		½–1	1.32	4.12	0.25	23.10	17.80	0.30	3.26	50.15
A_{22}		1–3	1.20	2.18	0.22	43.00	11.55	0.35	5.71	64.21
B_1		3–6	(As B_1 in profile above)							

* Analyses by G. H. Hough.

† Extraction with only 250 ml. 0.05 *N* HCl.

sodium saturated colloids in those layers have produced enough NaOH to raise the pH of the soil to about 9. Also the colloids have begun to move out of the upper layers and become flocculated beneath. It is interesting to note

that the major profile, number 3, has already started to solodize even before the development of a true A_1 horizon and while the soil as a whole is much more nearly a solonchak than a solonetz, from a morphological standpoint at least.

A few areas of rather uniform solonchak of the flooded type are to be found. These are developed in old ponded areas and usually from parent materials of heavy clay, either of lacustrine or alluvial origin. The following profile may be taken as typical of such solonchak:

*Solonchak (profile 6)**

A_1	0 to 1½″	Light gray fine sandy clay. This material is essentially a porous, brittle crust, friable with some difficulty to a dust.
A_2	1½ to 6″	Gray clay, fairly friable.
C	6″	Dark olive-gray clay, noticeably hard when dry but friable at ordinary moisture contents, grading in depth to friable material somewhat more grayish in color. There are numerous flecks of salt.

* Location: Section 17, T149N, R99W.

The vegetation on this soil consists chiefly of sage brush (*Artemisia cana*) and a scanty growth of salt grass, prostrate spurge (*Euphorbia glyptosperma*), and similar plants.

When such a soil develops into a solonetz it will obviously produce one of more uniform character than the puff solonchak.

The Second and Third Stages: The Solonetz-Complex

Of the hundreds of solonetz profiles examined by the writer, every one showed at least some solodization.

The following profile, developed from material laid down in an old ponded area, has very little solodization and the soil of the area is more nearly uniform in character than is usually the case. The native vegetation consists largely of western wheat grass.

*McKenzie clay, Solonetz (profile 7)**

A_1	0 to 1½″	Dark grayish brown clay loam, thoroughly permeated with roots.
A_2	1½ to 3″	Very dark grayish brown clay with a hard, coarsely granular structure.
B_2	3 to 14″	Brownish black clay with a very hard, prismatic structure. These prisms vary from 1 to 6 inches in diameter and break with difficulty into irregular, sharply angular pieces. In the upper part the soil is faintly mottled with rusty brown.
B_3	14 to 24″	Very dark gray clay. The prisms become much less distinct and the soil more massive.
C	24″—	Very dark gray massive clay. The soil digs out in large, massive chunks with difficulty. Only a few vertical cracks extend into this material.
		Large cracks extend from the surface down into the soil and into

these the surface soil falls, bringing about some mechanical mixing of the soil. The soil reacts with HCl only below 30 inches.

* Location: Section 30, T150N, R99W.

Profile 7 is not well developed, likely because of its youth and the extreme nature of the parent material. The soil must be classified as a solonetz developed from the flooded type of solonchak described under profile 6.

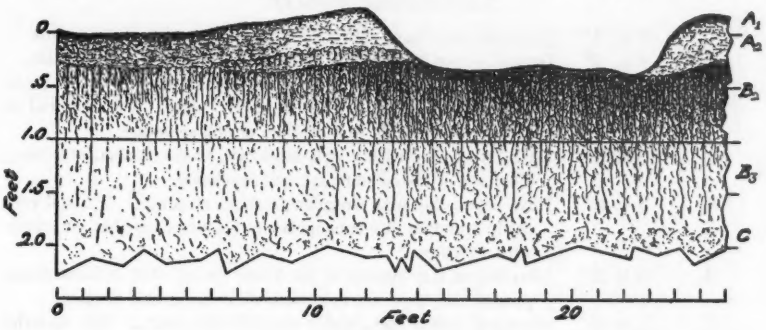


FIG. 4a

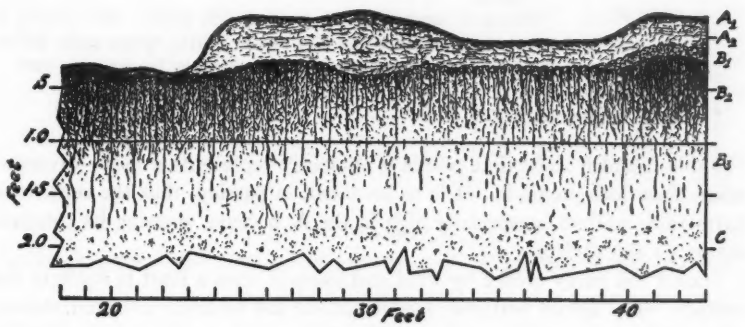


FIG. 4b

FIG. 4. CROSS SECTION, MADE TO SCALE FROM LEVEL NOTES, THROUGH AN ERODED SPOT ON THE SOLONETZ-COMPLEX

The two drawings overlap. Note that at the right of the section there is an old depression, now covered with buffalo grass and on the way toward reconstruction. In the freshly eroded spot note that the eluviated surface soil has been removed, exposing the heavy, intractable clay of the B horizon. Obviously a part of this fine material has been removed by wind just to the margin.

But by far the most common type of solonetz is the solonetz-complex. This complex may be associated with any one of a great variety of soil types, such as those developed from glacial till, from residual material, or from either local or general alluvium. In figures 4a and 4b is shown a cross section through an

eroded solodized solonetz spot occurring in a brown soil developed from glacial till. At the extreme right in the drawing is shown an old spot, now grassed over with buffalo grass (*Bulbilis dactyloides*), and in the stage of reconstruction back to the normal profile. This drawing was made to scale from an actual excavation in place. The profile just a few inches back from the margin of the eroded spot may be described as follows:

*Solodized solonetz (profile 8)**

A_1	0 to 1″	Brownish gray loam with a soft crumb or mulch-like structure.
A_2	1 to 3″	Grayish brown loam with a platy structure that is easily friable.
B_1	3 to 5″	Dull grayish brown silt loam. The soil shows relicts of an old prismatic structure but is distinctly platy. The material is rather easily friable to a medium crumb structure.
B_2	5 to 8″	Dark brown clay with a well-developed, hard columnar structure. The caps of the columns are well developed.
B_3	8 to 12″	Olive-brown clay with irregular prismatic structure. The soil very easily crumbles into subangular, nut-sized pieces that are friable with difficulty.
B_{31}	12 to 22″	Olive-brown clay similar to the above except that carbonates are present and there are numerous white flecks and streaks.
C_1	22 to 26″	Olive-gray sandy clay, highly mottled with white. This material is compact in place and digs out in brittle, rather easily friable pieces.
C	26″—	Olive-gray sandy clay till, mottled with white. The material is compact in place and digs out in brittle, rather easily friable pieces, but when these pieces are dry they become very hard.

* Location: Section 23, T150N, R100W.

Table 5 and 6 show that profile 9 obviously represents a more advanced stage than does profile 8. It is to be noted, in passing, that the content of extractable sodium is especially high in the A_1 horizon, showing its constant return to the surface.

Such a soil easily erodes by wind and water if once a start is made in the surface. The lighter textured, friable surface soil becomes removed, leaving exposed the dark, hard clay of the B horizon. Such a clay spot is shown in the cross section of figure 4. It is interesting to note that the puffed region in the solonchak-complex becomes the depressed area in the solonetz-complex. The native vegetation on the soils, as previously described, consists largely of grama grass with some other species, such as western wheat grass and needle grass. But in the eroded spot the first vegetation to come consists of such plants as cacti, especially *Opuntia fragilis*, salt grass, and salt sage. These plants are followed by western wheat grass and finally by buffalo grass. It is interesting to note that in this region, which is near the northern limit for buffalo grass, the majority of the stands of that grass are limited to these old eroded spots in the solonetz-complex.

As soon as the vegetation has again become established, surface soil horizons

begin to form from the old, exposed B horizon of the solodized solonetz. The profile through such a stage is described as follows.

*Reconstruction of eroded solodized solonetz (profile 10)**

A_1	0 to 1″	Grayish brown loam with a soft crumb or mulch-like structure.
A_2	1 to 2½″	Brownish gray friable loam.

TABLE 5

Mechanical analysis, pH, and $-d\,F\cdot P$ of solidized solenetz of the solonetz-complex, profiles 8 and 9

PROFILE	HORIZON	DEPTH	MECHANICAL ANALYSIS				$-d\,F\cdot P$	pH
			Sand above 0.05 mm.	Silt 0.005 to 0.05 mm.	Clay below 0.005 mm.	Clay below 0.002 mm.		
		inches	*per cent*	*per cent*	*per cent*	*per cent*	°C.	
8	A_1	0–1	42	40	18	10	0.015	7.6
	A_2	1–3	44	36	20	15	0.011	7.3
	B_1	3–5	40	36	24	16.5	0.015	7.35
	B_2	5–8	52	26	22	18	0.026	8.05
	B_3	8–12	38	19	43	35.5	0.076	8.6
	B_{31}	12–22	33	24.5	42.5	31	0.137	8.1
	C_1	22–26	61.5	16	22.5	17	0.130	9.25
	C	26+	68.5	15.5	16	12.5	0.139	9.35
Surface of the eroded spot		0–2	32	36.5	31.5	24	0.032	8.15
9	A_1	0–½	40	49	11	7.5	0.010	7.35
	A_2	½–5½	..	..	..	..	0.025	6.75
	B_1	5½–8	..	..	..	..	0.027	6.86
	B_2	8–12	37	37	26	19	0.021	7.1
	B_3	12–25	26	45	29	25.5	0.070	8.2
	C	25+	31	40.5	28.5	24	0.090	7.35

TABLE 6

Exchange material extracted from solodized solonetz, profile 9 by treatment with 0.05 N HCl*

(m.e. per 100 gm. soil)

HORIZON	DEPTH	SiO_3	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	TOTAL
	inches									
A_1	0–½	6.17	10.52	2.32	0.67	22.42	9.05	0.95	5.60	57.70
A_2	½–5½	5.44	9.03	2.31	0.56	22.52	6.97	0.98	2.59	50.40
B_1	5½–8	4.61	13.70	1.95	0.83	23.11	6.70	0.95	2.17	54.02
B_2	8–12	5.91	14.87	2.17	0.91	22.40	5.92	0.79	2.99	55.96
B_3	12–25	9.24	15.99	3.99	0.64	19.35	11.24	0.88	4.60	66.13
C	25+	8.93	19.85	4.80	0.24	21.58	9.70	1.14	7.18	72.42

* Analyses by G. J. Hough.

B_2	2½ to 9″	Dark brown clay with ill-defined prismatic structure, fairly easily friable to a medium crumb.
B_3	9 to 20″	Brownish olive clay with ill-defined prismatic structure, fairly easily friable.

The lower part of this profile is similar to that described under profile 8.

* Location: Adjacent to profile 8. This profile was taken through the old depression shown at the left in the cross section given in figure 4.

A great many variations in profile character are to be found in the solonetz-complex. On the one hand is the normal soil and at the other extreme is the solonetz developed from the flooded type of solonchak. When this latter type solodizes the A_2 horizon becomes strongly eluviated, as shown in the following description of profile 11. All gradations between may be observed. It would seem that in extreme cases of saturation with sodium salts during the solonchak stage the resulting solodized solonetz has a sharper profile: the horizons are more pronounced in their characteristics and the division between A and B is abrupt. Where the solonchak contains a smaller proportion of sodium, as compared to the divalent cations, the A horizon is less strongly eluviated and there are wide transitional horizons. These transitional layers show relicts of the old columnar structure as well as the characteristic platiness. Further, it may be that the type of vegetation which follows the solonchak is important. Plants which take in large amounts of sodium through their roots would tend to intensify the solodization process in the soil as compared to plants containing a smaller amount of this element.

In the case of solodization of the solonetz (profile 7) developed from the flooded type of solonchak (profile 6) the area is more uniform in original surface feature and in profile character. Such a soil does not exhibit the pronounced micro-relief characteristic of the solonetz-complex; there seems to be no differential erosion.

*Solodized-solonetz from flooded Solonchak (profile 11)**

A_1	0 to $\frac{3}{8}$″	Dark grayish brown very fine sandy loam.
A_2	$\frac{3}{8}$ to $4\frac{1}{2}$″	Brownish gray silt loam with well-developed platy structure, very friable and mellow.
A_{21}	$4\frac{1}{2}$ to 9″	Gray silty clay loam with well-developed, friable, platy structure. Some relicts of old columnar structure.
B_2	9 to 15″	Very dark brown clay with heavy, massive columns 2 to 4 inches in diameter. The soil breaks with difficulty into angular nut-sized fragments.
B_3	15 to 23″	Dark olive-brown clay with massive, poorly developed prismatic structure.
C_1	23 to 30″	Olive-gray, mottle with white, compact, friable clay.
C	30″	Olive-gray, friable clay, less strongly mottled with white than the above.

* Location: SW$\frac{1}{4}$. SW$\frac{1}{4}$. Section 35, T149N, R95W.

This profile represents the most advanced stage of solodization found by the writer in the entire area. The present vegetation on the soil consists of western wheat grass, grama grass, and similar species. The xerophytic and halophytic

plants, typical of the solonetz, have been entirely displaced by an association of plants very like that found on the normal soil. Unfortunately samples sufficient for mechanical analyses are not available. In table 7 are given the results for the depression of the freezing point and for pH. These values would indicate the soil to be rather close to a true soloth. In table 8 are shown the analyses of the HCl-extracts. Here it is noted that the calcium has greatly increased in the A_1 horizon but that the sodium has not. From these data, together with the morphology, it is evident that this profile is undergoing reconstruction.

On the basis of present studies it is possible to make up a general scheme of the genesis of the alkali soils for this section of the Great Plains. Such a scheme is shown in figure 5.

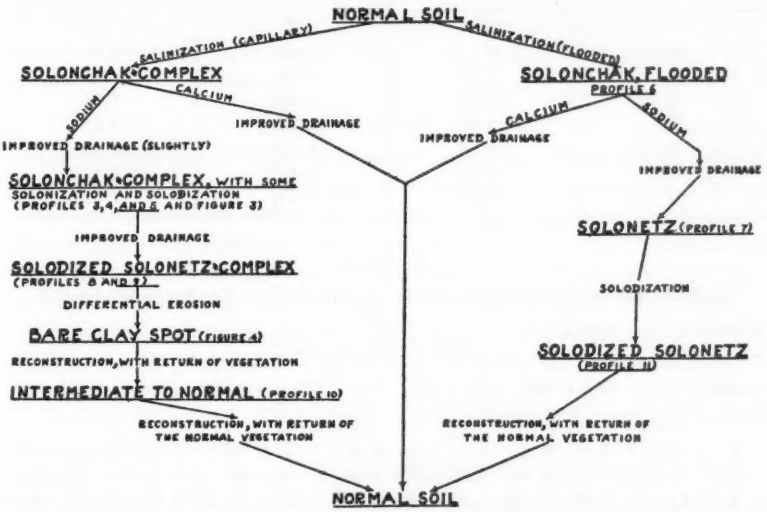


FIG. 5. AN OUTLINE OF THE CYCLE OF EVOLUTION OF THE ALKALI SOILS IN WESTERN NORTH DAKOTA

Importance of Vegetation

The vegetation on the soils of the solonchak and solonetz-complex consists of grasses or grass-like plants. That the character of the plants varies widely is well known. As a matter of fact the ash content and the relative percentages of different compounds in the ash vary more widely between various species of the semi-arid regions than do the characters between most timber types.

Nearly all data on mature profiles undergoing leaching show a concentration of bases in the A_1 horizon. In the case of salt-loving plants growing on sodium-solonchak, a large percentage of these bases are sodium and potassium. In the case of a solodized solonetz the A_1 horizon contains a large percentage of HCl-soluble sodium and, as shown in table 6, in a rather well-advanced

solodized solonetz the amount is considerably greater than in the primary leached horizon. Thus it can be seen that the sodium goes through the solum again and again; it is leached down and returned again to the surface. As with the bases in the case of a podzol there is a gradual loss of sodium to the ground water. As the process goes on halophytic vegetation is displaced by mesophytic plants using less sodium and more calcium. Slowly, as the development continues, sodium is replaced by hydrogen and calcium in the exchange and, finally, in the return to the normal soil, calcium (with magne-

TABLE 7

pH and −d F·P of solodized solonetz (profile 11)

HORIZON	DEPTH	−d F·P	pH
	inches	°C.	
A_1	0–$\frac{3}{8}$	0.017	5.7
A_2	$\frac{3}{8}$–4$\frac{1}{2}$	0.007	5.85
A_{21}	4$\frac{1}{2}$–9	0.018	5.85
B_2	9–15	0.023	7.35
B_3	15–23	0.037	8.15
C_1	23–30	0.048	8.45
C	30+	0.112	7.55

TABLE 8

Exchange material extracted from solodized solonetz, profile 11 by treatment with 0.05 N HCl*

(M.e. per 100 gm. soil)

HORIZON	DEPTH	SiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	TOTAL	C_2O	NET
	inches											
A_1	0–$\frac{3}{8}$	5.86	21.55	4.51	3.94	19.87	8.70	0.90	1.51	66.93	.....	66.93
A_2	$\frac{3}{8}$–4$\frac{1}{2}$	7.31	24.90	3.75	1.22	9.41	5.80	0.64	1.90	55.93	.....	55.93
A_{21}	4$\frac{1}{2}$–9	8.40	27.88	5.10	0.48	7.31	9.25	0.34	1.70	60.46	.....	60.46
B_2	9–15	8.35	25.29	3.82	0.56	12.06	12.67	0.54	3.78	67.19	.....	67.19
B_3	15–23	14.58	23.58	3.90	1.76	16.20	21.42	0.59	4.75	86.78	.....	86.78
C_1	23–30	19.24	52.67	12.02	1.13	50.71	14.25	0.88	4.31	155.21	50.90	104.31
C	30+	17.24	44.46	13.60	1.08	64.18	17.79	0.83	3.91	163.09	46.80	116.29

* Analyses by G. J. Hough.

sium) predominates. The rôle of the vegetation in the genesis of these soils can hardly be overemphasized.

Micro-Relief

One of the greatest points of interest in these soils, especially from a practical point of view, is the development of a pronounced micro-relief due to the differential erosin of the eluviated horizon of the solodized solonetz-complex. These spots do not appear in the solonetz soils developed from the more nearly

uniform solonchak of the flooded type, but as such uniformity is uncommon, nearly all of the solonetz is of the complex type and subject to differential erosion. The somewhat higher rims around these spots suggest that some considerable part of the erosion is carried on by wind action. The presence of small drainage channels from nearly every spot also suggests the influence of water.

Such a typical eroded spot as that shown in figure 4 is largely barren of vegetation. As a consequence, the grazing value of land having many of these spots is greatly reduced. As from 10 to 60 per cent of the land surface in many areas of otherwise good soil is occupied by such spots the importance of this feature is apparent. When these areas are plowed the soil in the spots is so poor in physical condition that plants make little or no growth. If care is taken to use manure on the barren areas, continued tillage tends to leaven them somewhat. But, in general, farmers are not inclined to break new land in such condition at present.

SUMMARY

The morphology of the solonchak and solonetz soils of western North Dakota were studied in order to understand their classification and genesis. It was found that normal soil, solonchak, solonetz, and soloth do not represent exclusive categories, either of morphology or of genesis. Such a soil as the solonchak-complex may show some characteristics of both solonetz and soloth; and nearly every solonetz shows some properties of solonchak or soloth.

The general cycle of the genesis of these soils from the normal soil, and back again to the normal soil, both for the complex types and the flooded types, is shown.

The great importance of the different kinds of vegetation in the evolution of these soils is emphasized.

Special attention is directed to the profiles of the solodized solonetz-complex. The differential erosion of the eluviated horizons of such soils gives rise to a pronounced micro-relief, greatly lowering the value of the land for either native or cultivated plants.

REFERENCES

(1) Bouyoucos, G. J. 1927 The hydrometer as a new and rapid method for determining the colloidal content of soils. *Soil Sci.* 23: 319–330.

(2) Bouyoucos, G. J., and McCool, M. M. 1915 The freezing point method as a new means of measuring the concentration of the soil solution in the soil. Mich. Agr. Exp. Sta. Tech. Bul. 24.

(3) Gedroiz, K. K. 1925 Soil absorbing complex and the absorbed soil cations as a basis of genetic soil classification. Nosovka Agr. Exp. Sta. Pub. 38. (Translation into English from the Russian by S. A. Waksman.)

(4) Kelley, W. P. 1922 Variability of alkali soil. *Soil Sci.* 14: 177–189.

(5) Kellogg, Charles E. 1930 Preliminary study of the profiles of the principal soil types of Wisconsin. Wis. Geol. and Nat. Hist. Survey Bul. 77A.

(6) Shutt, Frank T., and Macoun, John M. 1923 On the nature of burn-outs. *Proc. and Trans. Roy Soc. Canada.* (Third Ser.) 17: (sec. 3) 79–82.

(7) VILENSKY, D. G. 1932 Brief history and principal summary of saline and alkali soils in U. S. S. R. *Proc. Second. Internatl. Cong. Soil Sci.* (Leningrad, 1930) 5: 309–326.

(8) WILLIS, E. A., ROBESON, F. A., AND JOHNSTON, C. M. 1931 Graphical solution of the data furnished by the hydrometer method of analysis. *Pub. Roads* 12: 208–215.

(9) WINTERMYER, A. M. 1931 Procedure for treating soils for the determination of subgrade soil constants. *Pub. Roads* 12: 197–207.

PLATE 1

FIG. 1. A typical view of the solonchak-complex.

FIG. 2. A typical view of the solodized solonetz-complex.

FIG. 1

FIG. 2

AUTHOR INDEX

Abramson, H. A. Electrokinetic Phenomena and Their Application to Biology and Medicine (book review), 420.

Affleck, C. Application of the theory of probability to the size distribution of soil aggregates, 113–119.

Anderson, D. A. *See* **Walker, R. H.,** and Brown, P. E.

Anderson, M. S., and Byers, H. G. Carbon-nitrogen ratio in relation to soil classification, 121–138.

Baver, L. D. *See* **Winterkorn, H.**

Bennett, H. Practical Everyday Chemistry (book review), 423.

Bodenheimer, F. S., and Reich, K. Studies on soil protozoa, 259–265.

Bodman, G. B., and Edlefsen, N. E. Soil-moisture system, 425–444.

Boguslawski, E. von. Eilhard Alfred Mitscherlich—To the sixtieth birthday of the German investigator, 83–85.

Bouyoucos, G. J. Comparison between the pipette method and the hydrometer method for making mechanical analyses of soil, 335–345; method for determining the degree of decomposition that unknown decayed vegetable organic materials have already undergone in nature, 477–482.

Brown, P. E. *See* **Walker, R. H.,** Anderson, D. A., and.

Byers, H. G. *See* **Anderson, M. S.**

Chadwick, L. C. *See* **Laurie, A.**

Collings, G. H. Commercial Fertilizers. Their Sources and Use (book review), 418.

Corbet, A. S. Studies on tropical soil microbiology: II. The bacterial numbers in the soil of the Malay Peninsula, 407–416.

Cunningham, A. Practical Bacteriology (book review), 423.

Dhar, N. R. *See* **Tandon, S. P.**

Dowell, A. A., and Jesness, O. B. American Farmer and the Export Market (book review), 421.

Edlefsen, N. E. New method of measuring the aqueous vapor pressure of soils, 29–35; *see* **Bodman, G. B.**

Emmert, E. M. Rapid method for the determination of total nitrogen in soil, 139–142.

Farris, N. F. Root habits of certain crop plants as observed in the humid soils of New Jersey, 87–111.

Fieger, E. A., and Sturgis, M. B. Profile studies of the Coastal Prairie soils of Louisiana: I. Exchange and solution properties, 267–277.

Fowells, H. A., and Stephenson, R. E. Effect of burring on forest soils, 175–181.

Fred, E. B. *See* **Mehlich, A.,** and Truog, E.

Fresenius, L. *See* **Lemmermann, O.**

Godfrey, G. H. Indicator plants for measuring soil populations of the root-knot nematode, *Heterodera marioni* (Cornu) Goodey, 3–27.

Gopala Rao, G. Newer aspects of nitrification: I., 143–159.

Greaves, J. E. Arsenic content of soils, 355–362.

Heck, A. F. Effect of the degree of base saturation of a soil on its capacity to fix phosphorus in difficultly available form, 463–470.

Henrici, A. T. Biology of Bacteria. An Introduction to General Microbiology (book review), 418.

Jenny, H., and Leonard, C. D. Functional relationships between soil properties and rainfall, 363–381.

Jesness, O. B. *See* **Dowell, A. A.**

Joffe, J. S., and Kardos, L. T. Note on the determination of titanium in soils, 241–243.

Joffe, J. S., and Pugh, A. J. Soil profile studies: VI. Distribution of titanium in soils with special reference to podzols, 245–257.

Kardos, L. T. *See* **Joffe, J. S.**

Kellogg, C. E. Morphology and genesis of the solonetz soils of western North Dakota, 483–501.

Laurie, A., and Chadwick, L. C. Commercial Flower Forcing (book review), 417.

Lemmermann, O., and Fresenius, L. Methoden für die Untersuchung des Bodens (book review), 419.

Leonard, C. D. *See* **Jenny, H.**

McGeorge, W. T. Determination of phosphate availability in calcareous soils by electrodialysis, 347–353.

Mattson, S., and Pugh, A. J. Laws of soil colloidal behavior: XIV. The electrokinetics of hydrous oxides and their ionic exchange, 299–313.

Mehlich, A., Fred, E. B., and Truog, E. Cunninghamella plaque method of measuring available phosphorus in soil, 445–461.

Merkle, F. G. Base exchange studies on the Pennsylvania Jordan field plots, 37–64.

Paulie, E. Microflora of Kazakstan sands (central Asia), 401–406.

Pugh, A. J. Laws of soil colloidal behavior: II. Ionic exchange with hydroxides, 161–173; III. Colloidal phosphates, 315–334; *see* **Joffe, J. S.**; **Mattson, S.**

Ravikovitch, S. Anion exchange: I. Adsorption of the phosphoric acid ions by soils, 219–239; II. Liberation of the phosphoric acid ions adsorbed by soils, 279–290.

Reich, K. *See* **Bodenheimer, F. S.**

Scholz, H. F. *See* **Wilde, S. A.**

Shoemaker, J. S. Small-Fruit Culture (book review), 417.

Snider, H. J. Solubility of phosphorus in soils from some Illinois experiment fields, 471–476.

Spencer, V. E., and Stewart, R. Phosphate studies: I. Soil penetration of some organic and inorganic phosphates, 65–79.

Stephenson, R. E. *See* **Fowells, H. A.**

Stewart, R. *See* **Spencer, V. E.**

Sturgis, M. B. *See* **Fieger, E. A.**

Tandon, S. P., and Dhar, N. R. Influence of temperature on bacterial nitrification in tropical countries, 183–189.

Truog, E. *See* **Mehlich, A.**, Fred, E. B., and.

Vandecaveye, S. C., and Villanueva, B. R. Microbial activities in soil: I. Nitrogen fixation by Azotobacter and activity of various groups of microbes in Palouse silt loam, 191–205.

Villanueva, B. R. *See* **Vandecaveye, S. C.**

Walker, R. H., Anderson, D. A., and Brown, P. E. Physiological studies of Rhizobium: II. The effect of nitrogen source on oxygen consumption by *Rh. meliloti*, *Rh. trifolii*, and *Rh. phaseoli*, 207–217.

Wilde, S. A., and Scholz, H. F. Subdivision of the Upper Peninsula experimental forest on the basis of soils and vegetation, 383–399.

Willcox, O. W. Reshaping Agriculture (book review), 422.

Winterkorn, H., and Baver, L. D. Sorption of liquids by soil colloids: I. Liquid intake and swelling by soil colloidal materials, 291–298.

Wright, C. H. Soil Analysis. A Handbook of Physical and Chemical Methods (book review), 421.

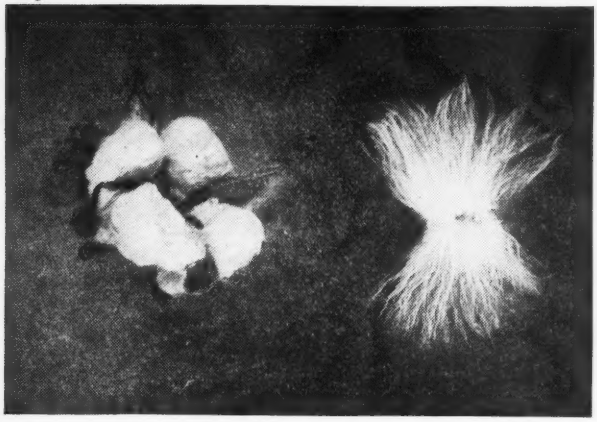
SUBJECT INDEX

Adsorption—
  anion, 163, 308.
  cation, 304.
  solubility and, 166.
Agriculture, Reshaping (book review), 422.
Alkaline, physiologically, salts, effect on phosphate liberation, 289.
American Farmer and the Export Market (book review), 421.
Ammonia—
  exchangeable, 42–56.
  oxidation of—
    as affected by catalysts, 147.
    photochemically, 144.
Anion—
  adsorption, 308.
  exchange in soils, 219–239, 279–290.
Arsenic content of soils, 355.
Azotobacter, nitrogen fixation by, 191.
Bacteria—*see* also Microbes.
  Biology of (book review), 418.
  numbers in tropical soil, 407.
  Rhizobium, oxygen consumption by, 207.
Bacteriology, Practical (book review), 423.
Base—
  exchange—*see* also Cation
    of hydroxides, 172.
    properties of coastal prairie soils, 267.
    studies on the Pennsylvania field plots, 37–64.
  exchange, as affected by—
    ammonium sulfate, 51.
    dried blood, 49.
    lime, 44, 54.
    manure, 43.
    nitrate of soda, 50.
    nitrogen carriers, 56.
    potash, 46, 54.
    salt water, 274.
    superphosphate, 46, 47.
  saturation—
    effect on phosphorus fixation, 463.
    method of determining, 38.
  saturation, as affected by—
    ammonium sulfate, 51.
    cropping, 42.
    dried blood, 49.
    lime, 44, 54.
    manure, 43.
    nitrate of soda, 50.
    nitrogen carriers, 56.
    potash, 46, 54.
    superphosphate, 46, 47.
  saturation, relation to—
    hydrogen-ion concentration, 464.
    rainfall, 375.
Bases—
  exchangeable—
    effect of treatments on, 37.
    in virgin and irrigated mounds, 273.
    method of determining, 40.
  nitrification effects on solubility of, 178.
Braunerde, titanium in, 255.
Calcium—*see* also Lime.
  exchangeable, 42–56.
  exchangeable, relation to phosphorus fixation, 465.
  glucose phosphate, penetration of, into the soil, 76.
  glycerophosphate, penetration of, into the soil, 76.
  glycol phosphate, penetration of, into the soil, 76.
  hydroxide, effect on phosphate release from soils, 280.
  saturated soil, phosphorus pentoxide absorption by, 225.
  sorbityl phosphate, penetration of, into the soil, 76.
Capillarity, *see* Moisture, capillary.
Carbon-nitrogen ratio in major soil groups of the U. S. A., 121–138.
Cation—
  adsorption, 304.
  exchange as affected by—
    calcium hydroxide, 280.
    sodium hydroxide, 285.
Chemistry, Practical Everyday (book review), 423.
Chernozem—
  carbon in profile of, 124.

Chernozem—(*continued*)
carbon-nitrogen ratio—
colloids of, 125.
soils, 124.
nitrogen in profile of, 124.
Climate, location of boundary between arid and humid, 379.
Clover, red, root development of, in humid soils, 99.
Colloids—
inorganic, amount of, as affected by rainfall, 371.
isoelectric point and ion exchange in, 162.
laws governing behavior of soil, 161, 299.
silica-sesquioxide ratio of, as a function of water intake, 296.
soil, sorption of liquids by, 291–298.
Corn, root development of, as affected by soil conditions, 103.
Cunninghamella plaque method for available phosphorus in soil, 445–461.
Daikuhara, Gintaro, obituary note on, 1.
Electrodialysis, phosphate availability as determined by the method of, 347–353.
Electrokinetic Phenomena and their Application to Biology and Medicine (book review), 420.
Fertilizers, Commercial (book review), 418.
Flower Forcing (book review), 417.
Forests, subdivision of, on basis of soils and vegetation, 383–399.
Fruit, Small-, Culture (book review), 417.
Humus, in burnt forest soils, 180.
Hydrogen—
exchangeable, 42–56.
exchangeable, relation to rainfall, 373.
saturated soils, adsorption of phosphorus pentoxide by, 220.
Hydrogen-ion concentration—
effect on—
microbial activity in soils, 201.
phosphoric acid adsorption by the soil complex, 230.
relation to—
ammonium sulfate, 51.
cropping, 42.
degree of saturation, 56.
dried blood, 49.
isoelectric precipitation of hydroxides, 301.
lime, 44, 54.
manure, 43.
nitrate of soda, 50.
nitrogen carriers, 56.
potash, 46, 54.
rainfall, 373.
superphosphate, 46, 47.
Hydroxides—
electrokinetics of, 299.
ionic exchange with, 161, 299.
Isoelectric—
point of a series of hydroxides, 300.
precipitation in the titanium-hydroxide system, 250.
Laterite soils, 132.
Lateritic soils—
carbon in profile of, 131.
carbon-nitrogen ratio in, 131.
genetic relation of, to podzolic soils, 250.
nitrogen in profile of, 131.
Lime, effect on—
liberation of phosphate, 289
nitrogen fixation, 194.
Magnesium, exchangeable, 42–56.
Manure, effect on nitrogen fixation, 194.
Microbes—*see* also Bacteria.
groups of, activity in soil, 191.
in Kazakstan sands, 401.
reaction effects on soil, 201.
Mitscherlich, E. A., to his sixtieth birthday, 83.
Mitscherlich method for phosphorus availability as compared with other methods, 457.
Moisture—
capillary potential of, relation to vapor pressure, 435.
mechanical forces, action on soil, 429.
movement in soil, 438.
soil system, 425.
Nematodes, root-knot in soils, 3.
Nitrates—
distribution of, at different depths, 154.
non-biological, formation of, 158.
Nitrification—
bacterial—
in tropics, 183–189.
versus chemical, 151.
calcium versus magnesium carbonate, effect on, 186.
chemical, 144, 187.
newer aspects of, 143–159.
studies in forest soils, 176.
Nitrite—
formation of, photochemically, 148.
oxidation of, to nitrates, 158.
Nitrogen—
fixation in soils, 191.

in—
chernozem, 124.
lateritic soils, 131.
podzolic soils, 129.
podzols, 128.
prairie soils, 126.
method of determining, in soils, 139–142.
nitric—
relation to radiant energy of sun, 156.
seasonal variation of, in atmosphere, 155.
organic and inorganic, photochemical oxidation, 152.
rainfall function relationships, 368.
Organic matter, degree of decomposition, method of determining, 477–482.
Phosphates—
availability of, 66.
availability of, as determined by electrodialysis, 347.
colloidal, study of, 315.
effect on base exchange, 46.
root zone distribution of, 69.
soil penetration of organic and inorganic, 65–79.
structure of, 316.
Phosphoric acid—
adsorption by soils, 219.
liberation of adsorbed, in soils, 279.
Phosphorus—
available, in soil, 445.
fixation of, 463.
solubility of, in soils, 471–476.
Plants, indicator for measuring population of nematodes in soils, 3.
Podzol—
analyses of, soils, 254.
carbon content of the, profile, 128.
carbon-nitrogen ratio of, 128.
nitrogen content of the, profile, 128.
soils, 387.
swampy, soils, 388.
titanium content of the, profile, 245.
Podzolic soils—
gray-brown—
carbon in profile of, 129–130.
carbon-nitrogen ratio, 129–130.
nitrogen in profile of, 129–130.
yellow and red—
carbon in profile of, 129–130.
carbon-nitrogen ratio, 129–130.
nitrogen in profile of, 129–130.
titanium in, 255.
Potassium, exchangeable, 42–56.
Potatoes—
root development of, in humid soils, 89.
yield of, as affected by spacing and seed piece, 98.
Prairie—
carbon-nitrogen ratio of, soils, 126.
coastal, soils, profile studies, 267–277.
Protozoa, soil, studies on, 259–265.
Rainfall, relation to soil properties, 363–381.
Red soils, titanium in, 255.
Rhizobium, *see* Bacteria.
Root—
clover (red), as affected by soil conditions, 99.
corn, as affected by soil conditions, 103.
habits of certain crop plants in soils of New Jersey, 87–111.
potato, as affected by—
fertilizers, 93.
seed piece, 94.
zone, distribution of nutrients within the, 69.
Silica-sesquioxide ratio, water intake as a function of, 296.
Sodium—
exchangeable, 42–56.
hydroxide, effect on exchangeable cations and anions, 285.
Soil—
acidity, relation to rainfall, 373.
aggregates, size distribution of, 113–119.
Analysis (book review), 421.
calcium saturated soil, 225.
classification, relation to carbon : nitrogen ratio, 121–138.
colloidal behavior, laws of, 161, 299, 315.
colloids, *see* Colloids.
formation, intensity of, 377.
hydrogen saturated, 221.
mechanical analysis of, comparison of methods, 335–345.
Methods of Investigation (book review), 419.
microbial activities in, 191–205.
moisture, *see* Moisture.
moisture system, 425–444.
Pennsylvania, fertility plots, studies on, 37.
phosphates—*see* also Phosphates, Phosphorus.
organic and inorganic, penetration of, 65.
release of adsorbed, 279.

Soil—(*continued*)
plots, Pennsylvania fertility, 37–64.
profile—
chernozem, 124.
lateritic, 131.
podzol, 128.
podzolic, 129.
prairie, 126, 267.
studies, 245–257, 267.
properties, relation to rainfall, 363.
protozoa, 259; *see* also Protozoa.
reaction, effect on microbial activity, 201.
root-knot nematode population in the, 3–27.
solonetz, *see* Solonetz.
sterilized, effect on ammonia oxidation, 152.
tropical, microbiology of, 407–416.
water table, disappearance of, 437.
Soils—
anion exchange in, 219.
arsenic content of, 355–362.
base saturation in, 38, 220.
Braunerde, *see* Braunerde.
calcareous, phosphate availability, 347.
chernozem, *see* Chernozem.
forest—
effect of burning on, 175–181.
management and, 391.
subdivision on basis of, 383.
gray-brown podzolic, *see* Podzolic soils.
humid, of New Jersey, root penetration as observed in, 87.
hydrogen-ion concentration, *see* Hydrogen-ion concentration.
hydrogen saturated, 221.
laterite, *see* Laterite.
lateritic, *see* Lateritic.
manured, effect on nitrogen fixation, 194.
muck, 389.
nitrogen in, *see* Nitrogen.
Palouse silt loam, microbial activities in, 191.
phosphoric acid liberation in, 279.
podzol, 387; *see* also Podzol, Podzolic soils.
prairie, *see* Prairie.
red and yellow podzolic, *see* Podzolic soils.
sandy, of Kazakstan, flora of, 401–406.
titanium determination in, 241.
unsaturated, 221.
vapor pressure of, method of measuring, 29–35.
yellow and red, titanium in, 255.
Solonchak, profile study of, 489.
Solonetz—
morphology and genesis of, 483–501.
solonchak stage leading to, 489.
Titanium—
determination of, in soils, 241–243.
distribution of—
in colloid fraction of various soils, 255.
in soils, 245.
effect on oxidation of ammonia, 148.
Unsaturation, effect on phosphate adsorption by the soil complex, 230.
Urea, oxidation of, photochemically, 152.
Vapor pressure—
curves of sand and clay, 427.
of soils, 29.
Vegetation—
as basis for subdividing forests, 383.
importance of, in saline soils, 497.
Water table, *see* Soil water table.
Yellow soils, titanium in, 255.



POTASH STARVATION SYMPTOMS

No. 1
in a series

THIS boll and lint sample shows the results of Rust, or potash hunger. It is typical of a plot that was fertilized with a complete fertilizer containing only 3% potash. The cotton rusted badly and yielded only 770 pounds of seed cotton per acre. Its lint, measured seven-eighths and was not uniform, with some long and some short fibers. A neighboring plot received the same fertilizer plus extra potash. It yielded 1,640 pounds of seed cotton per acre and its lint measured a full inch and was uniform high quality.

N. V. POTASH EXPORT MY., Inc., 19 W. 44th St., New York

—instructors in
SOIL SCIENCE
—and those engaged in scientific
SOIL RESEARCH

will find
the

PEERLESS
SOIL TUBE
Indispensable

Core samples obtainable
3 to 8 ft. deep in a few
minutes
Write now for details
Used by U. S. Dept. Agr.
Univ. of Calif.
Co. Farm Advisors

MADE BY
PARKER
MACHINE WORKS
3025 TWELFTH STREET
RIVERSIDE - CALIF.

2 IMPORTANT FERTILIZER MATERIALS

Both should be included in your experimental program

GRANULAR 'AERO' CYANAMID
AND
AMMO-PHOS* 11-48-0
HIGH-ANALYSIS FERTILIZER

Sufficient amounts of these materials for experimental purposes are supplied free on request.

** Reg. U. S. Pat. Off. and Prin. For. Countries.*

write **AMERICAN CYANAMID COMPANY**
New York, N. Y.

Manufacturers of
'AERO' CYANAMID and 'AMMO-PHOS'

SOIL SCIENCE

Manuscripts submitted for publication and communications concerning editorial matters should be sent to Dr. Jacob G. Lipman, New Jersey Agricultural Experiment Station, New Brunswick, N. J., U. S. A.

Correspondence concerning business matters should be addressed to The Williams & Wilkins Company, Publishers of Scientific Journals and Books, Mount Royal and Guilford Avenues, Baltimore, U. S. A.

Twenty-five reprints, without covers of articles will be furnished gratis to contributors when ordered in advance. A table giving cost of additional reprints, with an order slip, is sent with proof.

SOIL SCIENCE is issued monthly. Each issue consists of approximately 85 pages at present. Two volumes a year are issued at present. Each volume consists of approximately 500 pages.

Subscription price: $5.00 per volume in the United States and countries within the Postal Union. $5.50 outside the Postal Union.

Claims for copies lost in the mails must be received within 30 days (domestic), and 90 days (foreign), of the date of issue. Changes of address must be received at least two weeks in advance of issue.

New subscriptions and renewals are entered to begin with the first issue of the current volume. Should any issue of the current volume be out of print at the time the subscription order is received, the pro-rata value of such numbers will be credited to the next volume, and the renewal invoice therefore adjusted accordingly.

Subscriptions should be renewed promptly—To avoid a break in your series, subscriptions should be renewed promptly. The publishers cannot guarantee to supply back issues on belated renewals.

Subscriptions, new or renewal, should be sent to the Publishers or to Agents listed below.

Index for Volumes I-XXV is available at $3.00 so long as present supply lasts.

AGENTS

For Argentina and Uruguay: Beutelspacher y Cia, Sarmiento 815, Buenos Aires.

For Australia: Angus & Robertson, Limited, 89–95 Castlereagh Street, Sydney.

For Belgium: Henri Lamertin, 58 Rue Coudenberg, Bruxelles.

For the British Empire, except Australia and Canada: Baillière, Tindall & Cox, 8 Henrietta St., Covent Garden, WC. 2, London, England.

For Canada: Wm. Dawson & Sons, Ltd., 91 Queen Street East, Toronto.

For China: Commercial Press, Ltd., Paoshan Road, Shanghai, China.

For Denmark: H. Hagerup's Boghandel, Gothersgade 30, Kjöbenhavn.

For France: Émile Bougault, 48 Rue des Ecoles, Paris.

For Germany: B. Westermann Co., Inc., Zimmerstrasse 35–41, Berlin SW-68, Germany.

For Holland: Scheltema & Holkema, Rokin 74–76, Amsterdam.

For Japan and Korea: Maruzen Company, Ltd. (Maruzen-Kabushiki-Kaisha), 6 Nihonbashi Tori-Nichome, Tokyo; Fukuoka, Osaka, Kyoto, and Sendai, Japan.

For Spain: Ruiz Hermanos, Plaza de Santa Ana, 13, Madrid.

THE WILLIAMS & WILKINS COMPANY

Publishers of Scientific Books and Periodicals

BALTIMORE, U. S. A.

PUBLISHERS OF: *Medicine, Journal of Urology, Journal of Pharmacology and Experimental Therapeutics, American Journal of Tropical Medicine, Journal of Immunology, Journal of Industrial Hygiene, Quarterly Review of Biology, Journal of Bacteriology, Annals of the Pickett-Thomson Research Laboratory, Chemical Reviews, Soil Science, Social Forces, Personnel Journal, Journal of Comparative Psychology, Mental Measurement Monographs, Studies in Psychology and Psychiatry, Occupational Therapy and Rehabilitation, Child Development, The American Journal of Clinical Pathology, Journal of Physical Chemistry, Journal of the Biological Photographic Association, Philosophy of Science, Medico-Legal and Criminological Review.*